



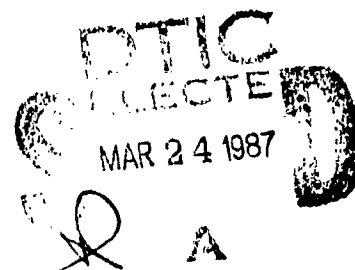
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HYBRID COMPOSITE RESPONSE TO HYDRAULIC RAM

Interim Report

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October 1986



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Prepared for

THE JOINT LOGISTICS COMMANDERS
JOINT TECHNICAL COORDINATING GROUP
ON
AIRCRAFT SURVIVABILITY

FOREWORD

This work was conducted under the Survivable Composite Structures program funded by the JTCG/AS Structures and Materials Subcommittee. Under this project, NWC (Naval Weapons Center), China Lake, Calif. was tasked with developing structural and material techniques for reducing hydraulic ram damage to composite aircraft structures. The testing and test panel construction was conducted by Code 3383 (Applied Research Branch) and support facilities at NWC. All tests were conducted between October 1985 and July 1986.

NOTE

This technical report was prepared by the Technology R&D Subgroup of the Joint Technical Coordinating Group on Aircraft Survivability in the Joint Logistics Commanders' organization. Because the Services' aircraft survivability development programs are dynamic and changing, this report represents the best data available to the subgroup at this time. It has been coordinated and approved at the JTCG subgroup level. The purpose of the report is to exchange data on all aircraft survivability programs, thereby promoting interservice awareness of the DoD aircraft survivability program under the cognizance of the Joint Logistics Commanders. By careful analysis of the data in this report, personnel with expertise in the aircraft survivability area should be better able to determine technical voids and areas of potential duplication or proliferation.

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<p>(U) Hydraulic ram is a major damage mechanism in fuel tanks that are impacted by projectiles. Composite materials have proved vulnerable to hydraulic ram in ballistic testing. Hybridizing graphite/epoxy structures with materials such as fiberglass, nylon, or Kevlar shows promise for reducing the vulnerability of composite structures to hydraulic ram. This report presents the results of ballistic testing of small test panels hybridized with several materials in several different configurations. Many configurations and materials provide significant improvement over baseline graphic panels and are recommended for further testing.</p> <p style="text-align: right;">graphite</p>					
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INTRODUCTION

BACKGROUND

Hydraulic ram is a major damage mechanism in fuel tanks that are impacted by high-speed projectiles. Hydraulic ram is a phenomena, whereby a projectile that travels through the fluid in the fuel tank generates pressure waves. The pressure waves can exceed 2500 psi in the near vicinity of the projectile. High-explosive incendiary projectiles, upon detonation, can create ram pressures in excess of 6000 psi. The hydraulic ram pressure waves are transient in nature; peak pressures rise and fall in a millisecond time frame. Peak pressure rapidly drops off with the distance from the projectile path or the high-explosive detonation; thus, the structure sees a very local and transient pressure wave.

The magnitude of the hydraulic ram pressures and the subsequent damage is dependent on many variables. The major variables that influence structural damage as a result of hydraulic ram are

1. Projectile velocity—Hydraulic ram induced by non-detonating projectiles is caused by fluid drag on the projectile; thus the higher the projectile velocity, the higher the hydraulic ram pressure will be.
2. Projectile tumbling—When a projectile tumbles, it presents a larger drag area. Since hydraulic ram is caused by fluid drag, the larger the projectile presented area, the higher the pressure will be.
3. Fuel tank size—A small fuel tank generally suffers more hydraulic ram damage than a large tank. Since the hydraulic ram pressure drops rapidly with distance, there is a lower average pressure on the walls of a large tank.
4. Tank structural design—The geometry and structure design philosophy can greatly influence the damage inflicted on the structure by the hydraulic ram pressure. Structures designed to be elastic, or fail at predetermined "soft" failure points, will generally exhibit lower damage.
5. Tank materials—Tank materials can also greatly influence the damage inflicted by the ram pressure. A brittle material such as graphite is more likely to fail catastrophically than a ductile metal that is capable of plastic deformation.

The subject of this research is the tendency for graphite structures to fail in a brittle manner. Composite structures are becoming more prevalent in the aircraft industry. Each new generation of aircraft has a higher percentage of composite parts. The V-22 and most future aircraft will be 75 to 80 percent composite. The fuel tanks of these aircraft will need to survive hydraulic ram induced damage.

OBJECTIVE

The Survivable Composite Structures program is tasked with investigating various structural and material methods that reduce hydraulic ram damage to composite aircraft structures. This portion of the program focuses on the effects of hybridizing composite panels to reduce ram damage. The objective is to determine what hybridizations will give the greatest damage reduction for the lowest weight penalty.

TEST PHILOSOPHY

To determine the hybridization that would give the greatest damage reduction for the least weight penalty, a two-phase program was initiated. In phase one, a wide variety of hybridizations were investigated by shooting 12-inch-diameter flat circular panels under carefully controlled conditions. Each panel was designed with the same graphite lay-up and resin system; the only alteration between panels was the hybridizing material added or the technique of hybridization. Projectile velocities were kept constant for an individual test series. The tests were designed to compare one hybridization against another—not to give quantitative values of damage reduction.

The small-scale 12-inch-diameter tests were designed to identify promising hybridization concepts quickly. Those hybrid concepts which showed the most promise will be tested on larger, more realistic test specimens in phase two. This testing will incorporate full-scale panels with realistic structural attachments, focusing on comparisons of the hybridization concepts, and producing quantitative data on damage reduction to specific threats.

12-INCH-DIAMETER PANEL TESTS

TEST SETUP

The test apparatus shown in Figures 1 through 5 was used to simulate hydraulic ram due to projectile penetration of a fuel tank. The hydraulic ram simulator tank is shown from the exit side in Figure 1. The steel and aluminum tank walls are 1/2 inch thick and 2 feet square. The tank has a free surface on the top and a 10-inch-diameter hole in the exit side. The 12-inch-diameter test panel is clamped over this opening with a 1/2-inch-thick steel ring, which in turn, is bolted to the exit wall. A 1-inch-wide ring around the outside of the panel is clamped, leaving a 10-inch-diameter area exposed on both sides. Figure 2 shows this ring being removed after a test shot. Note the chipped paint on the panel that outlines the area exposed to the hydraulic ram. The projectile enters the tank of water through a replaceable 1 1/2-inch rubber membrane. The entrance port is visible through the top of the tank in Figure 3 (rubber membrane is not in place). The round's velocity is determined by a timing trap located in front of the simulation tank (Figure 4) and is read out on a Hewlett-Packard 5328A universal counter. The gun is constructed so that the gases caused by firing are vented out of the barrel. Only the projectile enters the tank. Figure 5 shows the gun and the breach being assembled.



FIGURE 1. Hydraulic Ram Simulator Tank.

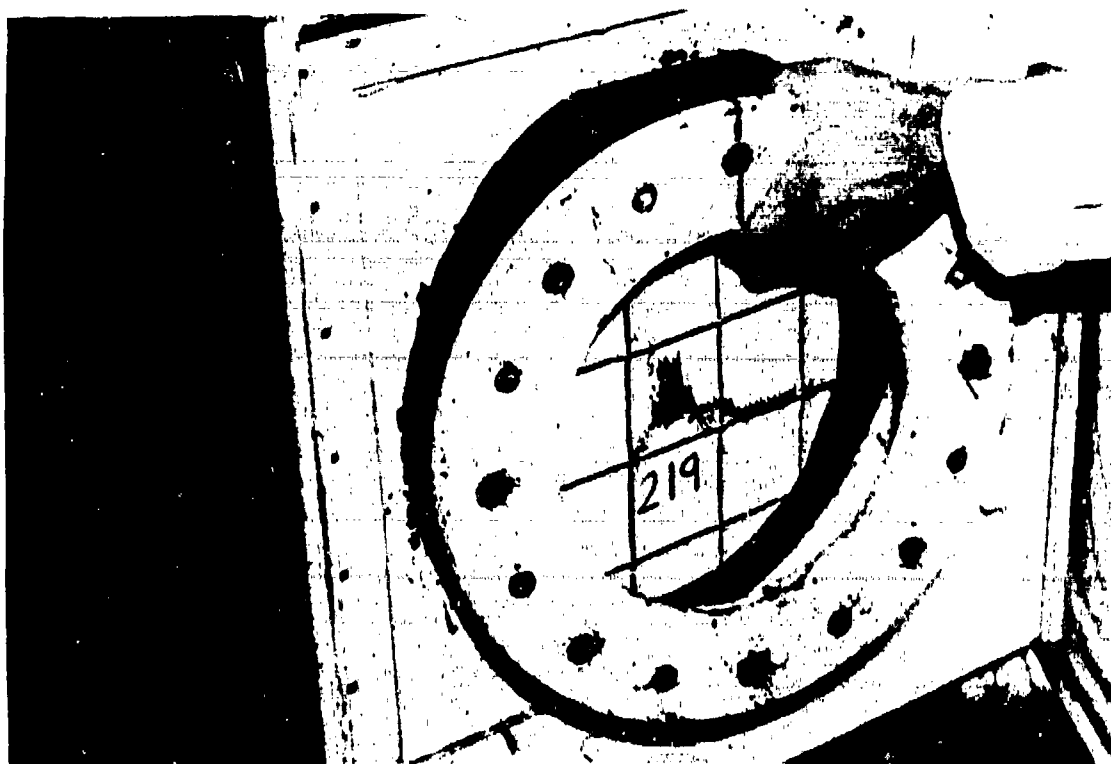


FIGURE 2. Clamping Ring.



FIGURE 3. Simulator Tank Entrance Port.

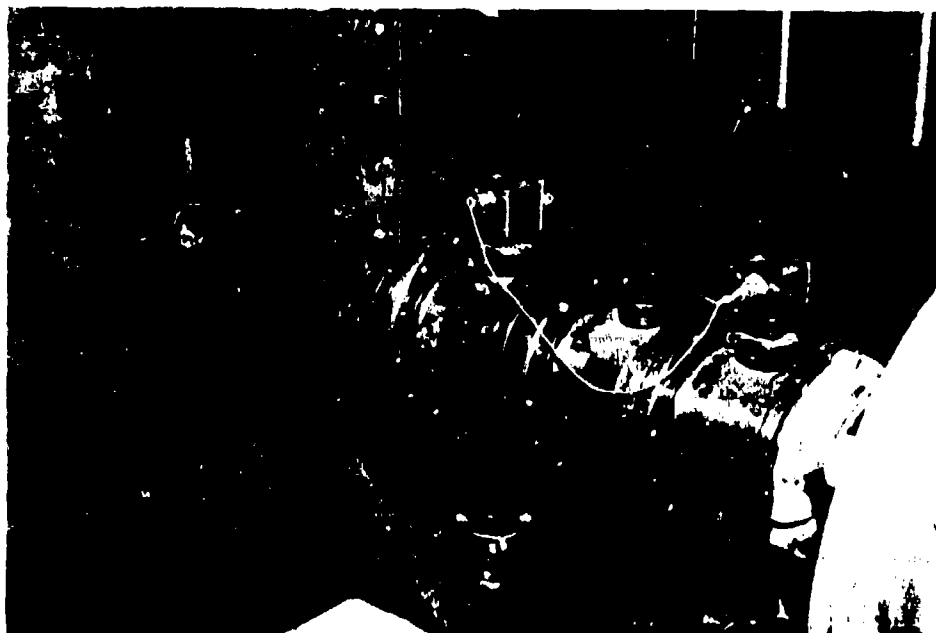


FIGURE 4. Timing Trap Attached To Gun Muzzle.

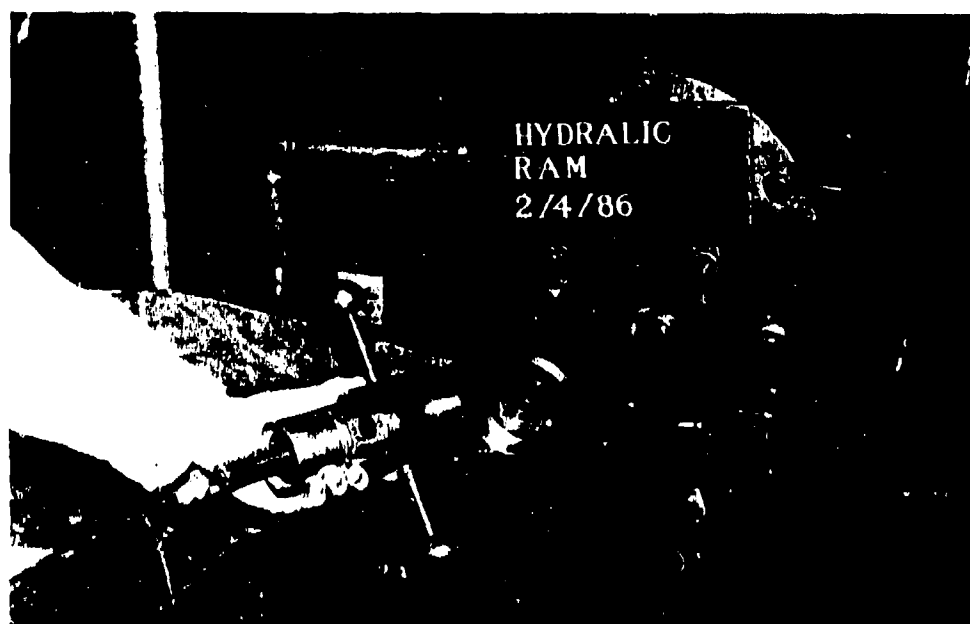


FIGURE 5. 50-Caliber Gun and Screw-in Breech.

The projectile used in these tests was a blunt 50-caliber right-circular cylinder. A blunt cylinder was used because a pointed projectile, when entering a fluid, may tumble unpredictably, striking the panel at a random angle, thereby causing inconsistent penetration damage. However, a blunt projectile of proper dimensions will not tumble and will yield consistent impacts on the test panels.

TEST PANEL FABRICATION

When exploratory testing is performed, a fixed variable needs to be established from which other variables can be changed and the results measured. This testing assumes a base composite structure of five layers of woven 6K denier, five-harness satin graphite cloth oriented 0-90/ \pm 45/0-90/ \pm 45/0-90. Added to this in several configurations are various hybridizing materials, which are placed between layers of the base graphite or are added as an outside layer. Three basic configurations of the hybridizing materials were used; cords, strips, and layers. Some materials did not lend themselves to all three configurations, and thus were tested only in the appropriate configurations.

The first configuration consisted of cords placed in a grid pattern between the third and fourth layers of the base graphite. In this configuration, grids were laid with single or double cords with 1- and 3-inch spacing, respectively. The double cords were used on the 3-inch spacing to be comparable in weight to the single-cord grids that used the 1-inch spacing. All grids were laid on the 0-90 axis.

The strip configuration also used a grid pattern. Two or three grids of 1-inch-wide material were laid down either spaced out between several layers, or all between two layers of the base graphite. All grids were laid on the 0-90 axis, with a 3-inch spacing. Two grids were used if the material used was considered to be high weight, while three grids were used if the material was considered to be low weight. This was done to keep the different test panel weights approximately the same.

The last basic configuration was simply a complete layer of material added either between layers of the base graphite or as an outside layer. Kevlar and Spectra layers were co-cured with the graphite, while foam and rubber layers were adhesively bonded after curing.

Also included in the first series of panels were "miscellaneous" configurations. One that was tested in the miscellaneous category involved attaching stringers, made of two layers of graphite, to the baseline panel. The stringers were 8 inches long, 1 inch wide, and 1/2 inch high with a 1/2-inch flange along the perimeter for mounting to the test panel. Each panel had two stringers placed 4 inches apart that were adhesively bonded to the panel with epoxy. Also analyzed under the miscellaneous category were two panels made by Phillips 66 with Ryton thermoplastic

resin. Thermoplastic resins are "tougher" than thermoset resins, as they absorb more energy in fracturing, and therefore, should be less vulnerable to a given impact threat level. One panel contained all graphite and the other an additional layer of Kevlar.

All other panels used an Epon 828 equivalent resin and were pressure rolled to remove voids and excess resin. Each panel was cured in a vacuum bag at 175°F for 90 minutes and cut into 12-inch-diameter disks. The specific materials used in these panels are described in Table 1.

TABLE 1. Test Panel Materials.

Material	Description
Matrix resin	
West Resin 105 Ryton	Epon 828-equivalent resin system Polyphenylene sulfide thermo- plastic
Cloth	
Graphite	Celion 600, 6K denier, five- harness satin weave
Kevlar 29	9.4 oz/yd ² , plain weave
E-Glass	6.0 oz/yd ² , plain weave
Nylon	11.7 oz/yd ² , plain weave
Spectra 900	Polyethylene material, 7.0 oz/yd ² , plain weave
Spectra 1000	Polyethylene material, 6.0 oz/yd ² , plain weave
Cord	
Kevlar 29	3/32-inch diameter, braided
Nylon	1/8-inch diameter, braided
E-Glass	1/8-inch diameter, braided
Additional materials	
Styrofoam	2 lb/ft ³ , closed cell
Self-vulcanizing rubber	1/8 thick

EVALUATION TECHNIQUES

The purpose of this test program was not to examine a design for a particular aircraft. The test panels are generic and were designed to be compared only to each other to establish a relative survivability/vulnerability ranking. The merit of a particular hybridization technique was evaluated based upon its comparison with other techniques. This project seeks to rank both materials and configurations in a relative survivability order and identify the least vulnerable configurations.

The damage ranking criteria was determined by three concentric damage zones of 4-, 8-, and 12-inch diameters. These zones were centered on the point of impact. If the damage was contained within the 4-inch zone it was considered minor, within the 8-inch zone—moderate, and beyond the 8-inch zone—severe. If a test panel had no residual structural value or was removed from the test fixture in two or more pieces, it was considered a drastic failure.

Two types of damage were evaluated, cracks and delamination. A crack is the tearing of the structure accompanied by local splintering along the crack line. This splintering extends about 1/4 inch on either side of the crack. Cracks were measured by visual observation of the panel. Delamination is the separation of two or more layers of the panel. The extent of a delamination is determined by a coin-tap test. When a coin is tapped on the surface of a delamination, it produces a noticeably different sound than when tapped over a solid layup. Both cracks and delaminations are measured and, depending on the zone they extend to, are rated minor, moderate, or severe.

In addition to cracking and delamination, there are two other types of damage observed when using small test specimens—edge cracking and edge shearing. Edge cracking is a phenomenon caused by the test fixture in which damage extends from the edge of the panel toward the penetration hole but stops before reaching the hole. Edge cracking is experienced only by panels with cords. In edge shearing, the cracking extends along the inside of the ring where the panel is clamped. This is caused by the hydraulic ram energy trying to shear out the entire 25-inch circumference of the inside of the clamping ring. No attempt is made at rating the extent of the damage done by these two mechanisms; it is simply noted.

100 SERIES TESTS

The purpose of the 100 series testing was to determine which structural configurations and which materials displayed promising survivability characteristics from a wide variety of test panels, and to quickly eliminate ineffective, vulnerable concepts. The basis for eliminating a concept from further testing was to compare the damage sustained by the concept panel to the damage sustained by a plain composite panel.

This baseline panel is composed of six layers of graphite cloth arranged 0-90/ \pm 45/0-90/ \pm 45/0-90/ \pm 45 in an epoxy matrix. Any concept showing damage equal to or greater than the plain composite panel was dropped from further testing. Figure 6 shows how the baseline panel brittly cracked out to and around the clamping ring. This is common in composites impacted by hydraulic ram. Figure 7 shows the damage caused by hydraulic ram to a 7075-T6 aluminum plate of approximately the same thickness as the composite panels. Notice the yielding of the plate in this more ductile material.

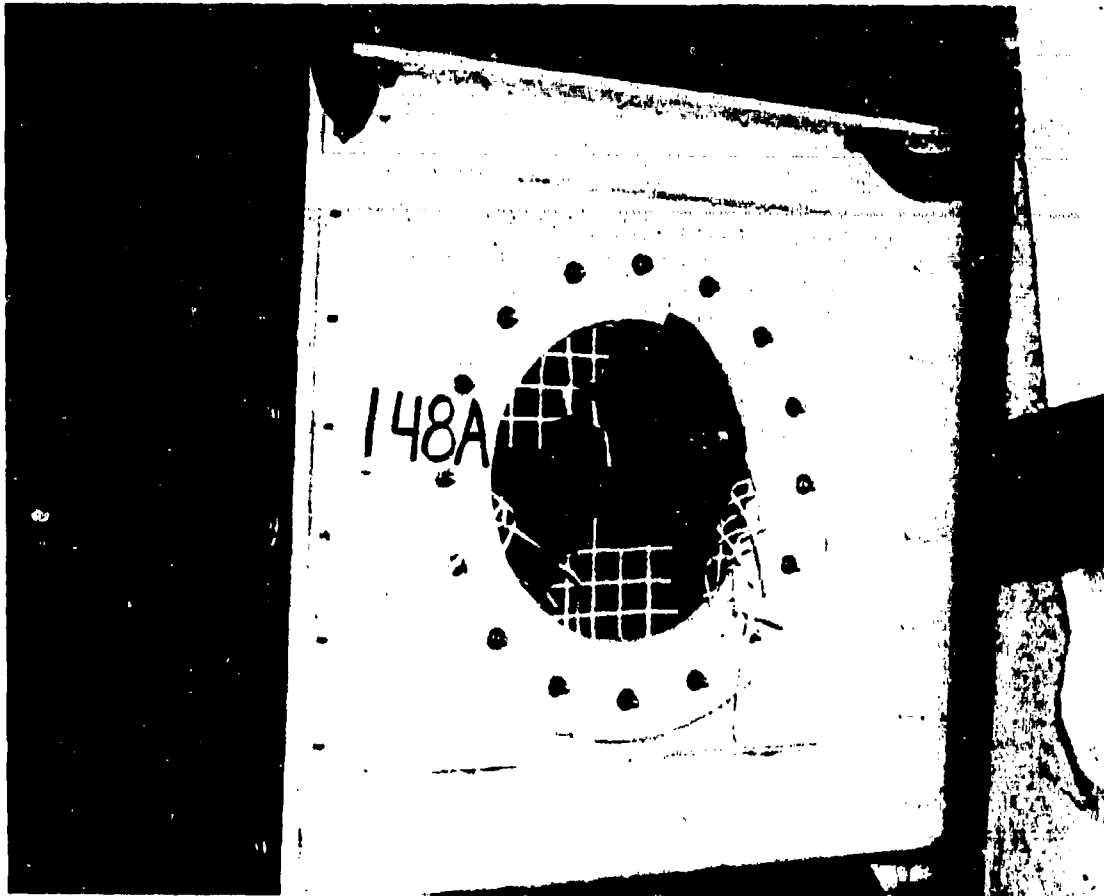


FIGURE 6. Damage Sustained by Baseline Graphite/Epoxy Panel From 1500-ft/sec Threat.



FIGURE 7. Damage Sustained by 7076-T6 Aluminum Plate From 1500-ft/sec Threat.

Test Results

The 100 series tests eliminated several concepts from further testing. The electrical grade fiber glass (E-Glass) strip configuration panel failed (Figure 8), as did the panel with grids of hand braided E-Glass cord. Another concept that failed was a sandwich structure of self-vulcanizing rubber, in which a layer of rubber was glued between precured graphite layers (Figure 9). The adhesively bonded graphite stringer concept (Figure 10) was also eliminated. The adhesive bond between the stringers and the panel failed, which left essentially a baseline panel. Figure 11 shows the extent of the stringer separation from one of these panels. The Ryton thermoplastic panels produced by Phillips 66 were also drastic failures (Figures 12 and 13). The performance of all the panels tested in the 100 series is presented in Table 2.

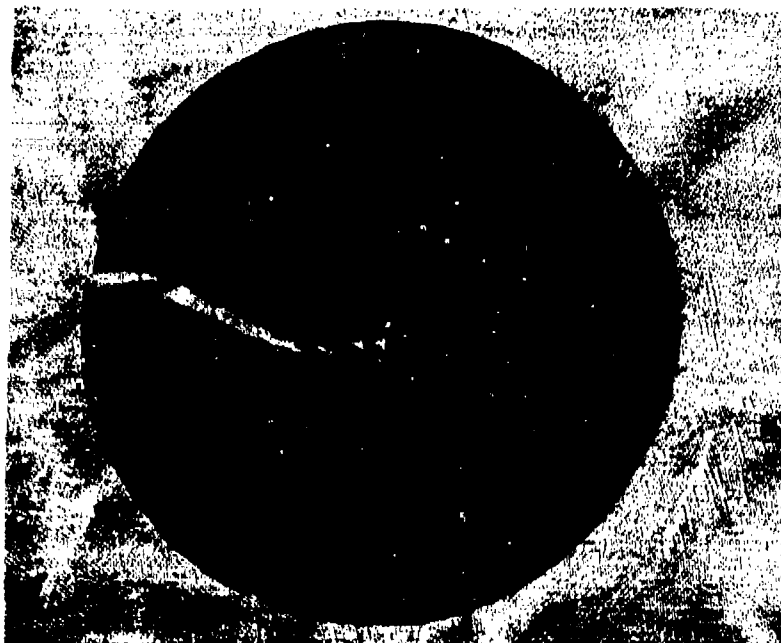


FIGURE 8. Damage Sustained by E-Glass Strip Grid Panel.

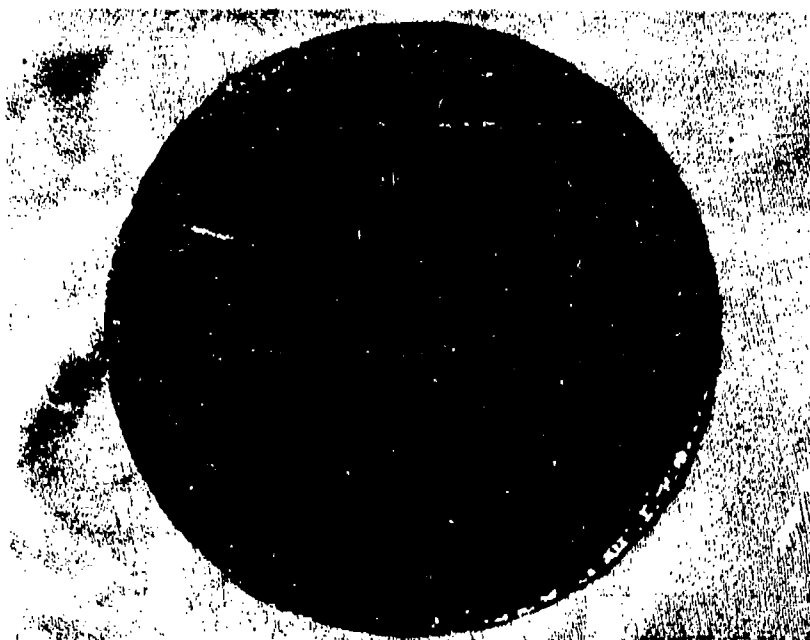


FIGURE 9. Damage Sustained by Self-Vulcanizing Rubber Panel.



FIGURE 10. Damage Sustained by Panel With Adhesively Bonded Stringers.

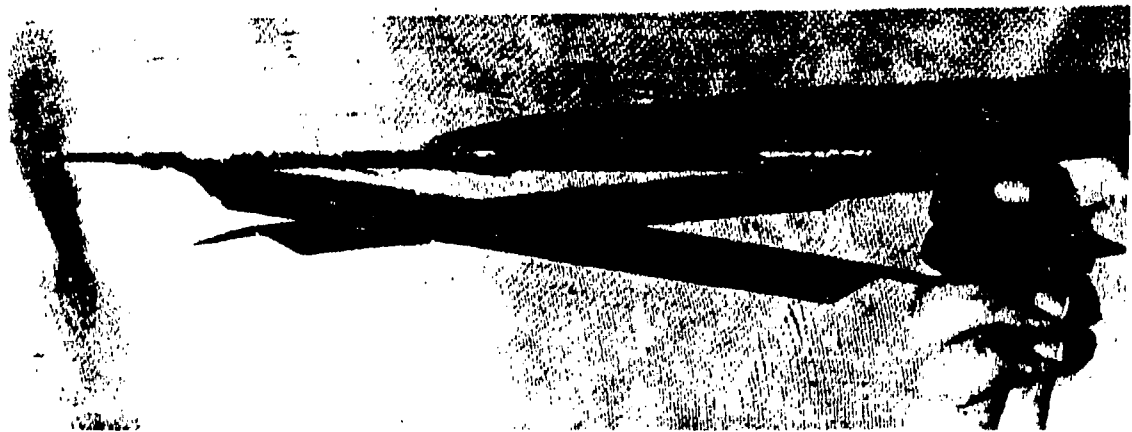


FIGURE 11. Stringers Debonded From Panel.

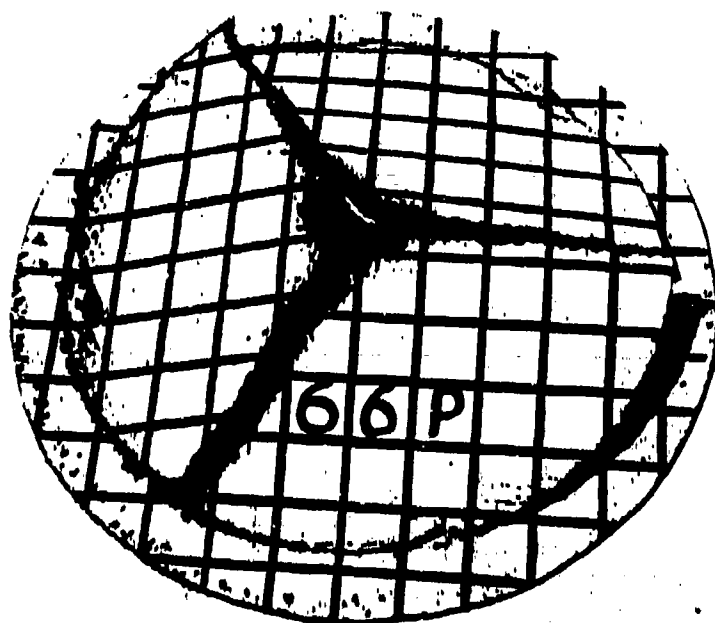


FIGURE 12. Damage Sustained by Ryton Thermoplastic Panel.

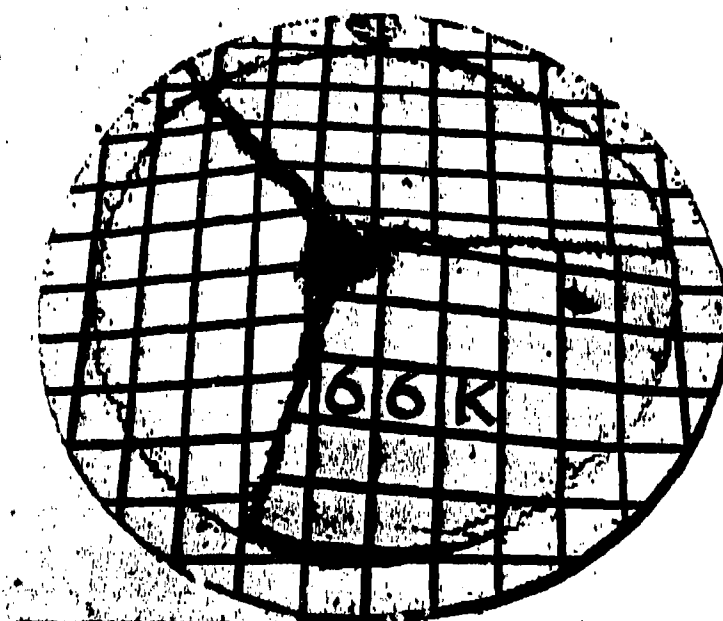


FIGURE 13. Damage Sustained by Ryton Thermoplastic Panel With Kevlar Layer.

TABLE 2. 100 Series Test Results.

Panel	Description	Weight, gm	Velocity, ft/s	Results
Baseline				
148A	6 layers of graphite	273	1578	Drastic failure, edge shear
148B	Same as 148A	273	1506	Drastic failure, edge shear
Cord grid				
125	Double Kevlar cord	270	1448	Moderate cracking, minor delamination
126	Same as 125	265	1480	Moderate cracking, moderate delamination
127	Same as 125	224	1410	Minor cracking, minor delamination, edge cracking
130	Single Kevlar cord, 3-inch spacing	220	1519	Severe cracking, minor delamination
131	Same as 130	220	1564	Drastic failure
136	Same Kevlar cord, 2-inch spacing, woven into graphite	319	1518	Moderate cracking, minor delamination
137	Same as 136	327	1510	Drastic failure
138	Same as 136	338	1516	Moderate cracking, minor delamination
152	E-Glass tows, 3-inch spacing	278	1490	Severe cracking, moderate delamination
153	Double nylon cord, 3-inch spacing	208	1455	Minor cracking, edge cracking

TABLE 2. (Contd.)

Panel	Description	Weight, gm	Velocity, ft/s	Results
Layers				
128	Kevlar	284	1410	Minor cracking, minor delamination
129	Same as 128	297	1422	Minor cracking, minor delamination
132	Nylon	305	1465	Severe cracking, minor delamination
133	Same as 132	303	1522	Severe cracking, minor delamination
134	Kevlar as last layer	277	1535	Moderate cracking, severe delamination
135	Same as 134	288	1492	Moderate cracking, severe delamination
147	1/4-inch foam	348	1465	Drastic failure
151	Same as 147	310	1480	Moderate cracking, moderate delamination
149	1/2-inch foam as last layer	390	1545	Minor cracking, minor delamination
150	1/4-inch foam as last layer	317	1543	Drastic failure
158	Self-vulcanizing rubber cured at 275°F	341	1520	Severe cracking, minor delamination
159	Same as 158 except cured at 350°F	345	1520	Severe cracking, severe delamination

TABLE 2. (Contd.)

Panel	Description	Weight, gm	Velocity, ft/s	Results
Strip grid				
139	Two Kevlar strip grids, 1-inch wide, 3-inch spacing	320	1498	Moderate cracking, moderate delamination
140	Same as 139	308	1568	Minor cracking, minor delamination
141	Same as 139	313	1425	Moderate cracking, minor delamination
142	Two Kevlar strip grids, 1-inch wide, 3-inch spacing on separate layers	317	1542	Moderate cracking, minor delamination
143	Same as 142	313	1509	Severe cracking, minor delamination
144	E-Glass strip grids, 1-inch wide, 3-inch spacing	289	1550	Drastic failure
145	Same as 144	305	1486	Drastic failure
146	Same as 144	283	1455	Drastic failure
Miscellaneous				
66P	Ryton thermo-plastic	181	1563	Drastic failure
66K	Ryton with Kevlar layer	197	1500	Drastic failure
154	Graphite stringers, adhesively bonded	264	1520	Drastic failure
155	Same as 154	248	1405	Drastic failure
157	Same as 154	262	1550	Drastic failure
156	Graphite stringers and 1/4-inch foam, adhesively bonded	247	1514	Severe cracking, severe delamination

200 SERIES TESTS

The 200 series tests were shot at a nominal 1900-ft/sec velocity. The 200 series tests provided a more serious threat to the concepts that survived the 100 series. The higher velocity was intended to cause more extensive damage to the panels so that the differences between the panels would be more apparent. Figure 14 shows the baseline graphite panel for the 200 series tests. This panel contains five layers of graphite cloth arranged 0-90/±45/0-90/±45/0-90.

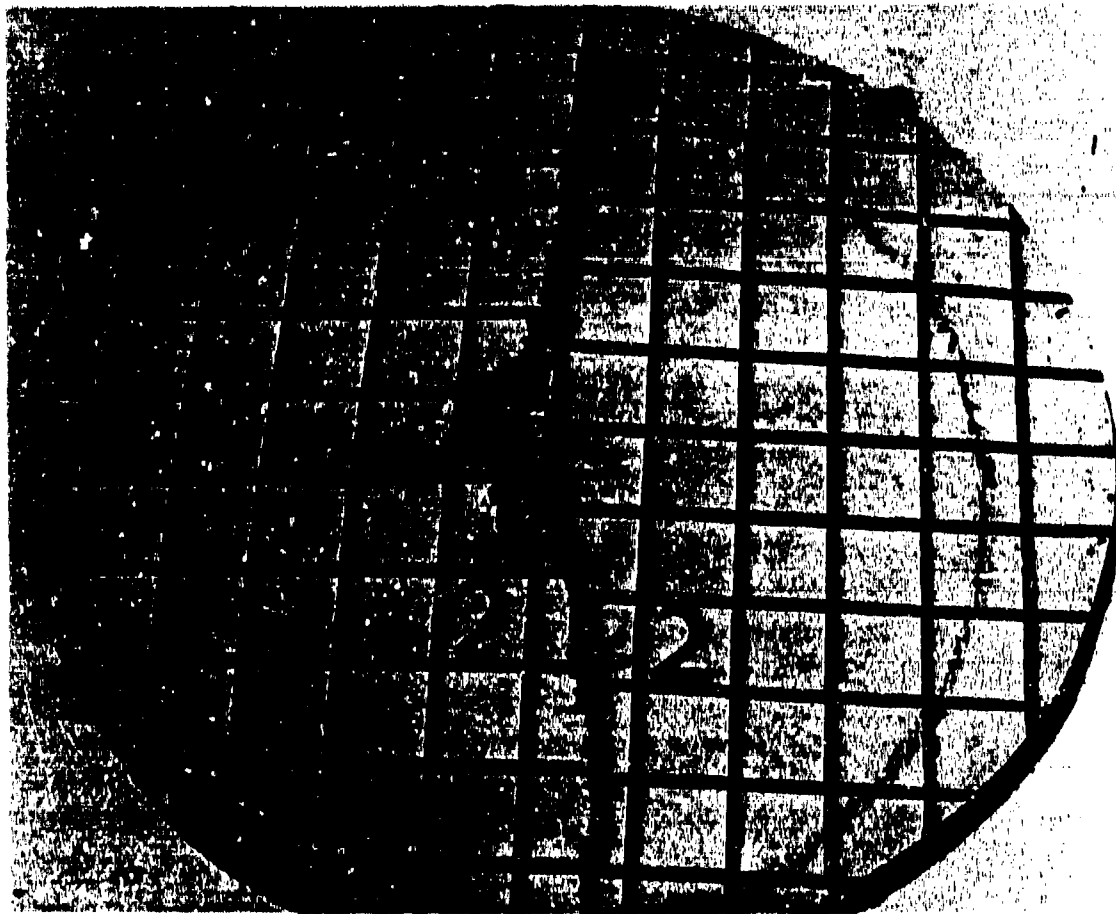


FIGURE 14. Damage Sustained by 200 Series Baseline Panel.

Test Results

Cords. The two different configurations of cords tested in the 200 series were a double-cord grid arranged at a 3-inch spacing (panels 203, 206, and 219), and a single-cord grid arranged at a 1-inch spacing (panels 206 and 220). The 1-inch spaced panels showed some indication of being better able to prevent cracks, while the 3-inch spaced panels experienced less delamination. These comparisons are somewhat suspect. Due to fabrication problems, the 1-inch grids were placed under the last layer of graphite only, while the 3-inch grids were placed under two layers. This discrepancy may have allowed the 1-inch grid panels to delaminate more easily than they might have under two graphite layers.

As for the cord materials, Kevlar and Nylon appeared to achieve about the same survivability increase. Since Kevlar has a tensile strength many times higher than nylon, it appeared that the decrease in cord vulnerability was not related to ultimate strength. Neither cord broke, except when struck directly by the round, and both the Kevlar and Nylon experienced the same amount of delamination. Table 3 shows the results of each test. Table 4 shows the relative survivability of the most successful cord grid panels. Figures 15 through 18 show these panels in descending order, from least vulnerable to more vulnerable.

Strips. There was no difference observed in the strip grid concept between laying all strips together between two layers and spreading them out through the thickness of the layup. Both of these configurations used 1-inch-wide strips, spaced in a 3-inch grid.

Spectra 1000 (panels 226 and 227) showed the most survivability in the strip configuration. The Kevlar panel (No. 213) cracked and tore through two of the three horizontal lengths; the center length was torn by the round, and one outer length was torn by the ram effects. The only strips torn in the Spectra 1000 panel were the strips that were struck by the round. Spectra 900 (panels 207 and 208) experienced greater cracking than either Spectra 1000 or Kevlar. Both panels of Spectra 900 experienced slightly more delamination than the Spectra 1000.

TABLE 3. 200 Series Cord Grid Panel Results.

Panel	Description	Weight, gm	Velocity, ft/s	Results
200	Double Kevlar cords, 3-inch spacing	201	1506	Minor cracking, minor delamination, edge cracking
201	Same as 200	208	1700	Minor cracking, minor delamination, edge cracking
202	Same as 200	204	1798	Minor cracking, minor delamination, edge cracking
203	Same as 200	203	1920	Severe cracking, minor delamination, edge cracking
206	Single Kevlar cord, 1-inch spacing	219	1920	Severe cracking, minor delamination, edge cracking
216	Double nylon cords, 3-inch spacing	205	1988	Severe cracking, minor delamination
219	Same as 216	211	1920	Severe cracking, minor delamination
220	Single nylon cord, 1-inch spacing	227	1880	Severe cracking, moderate delamination

TABLE 4. Ranking Table, Cords.

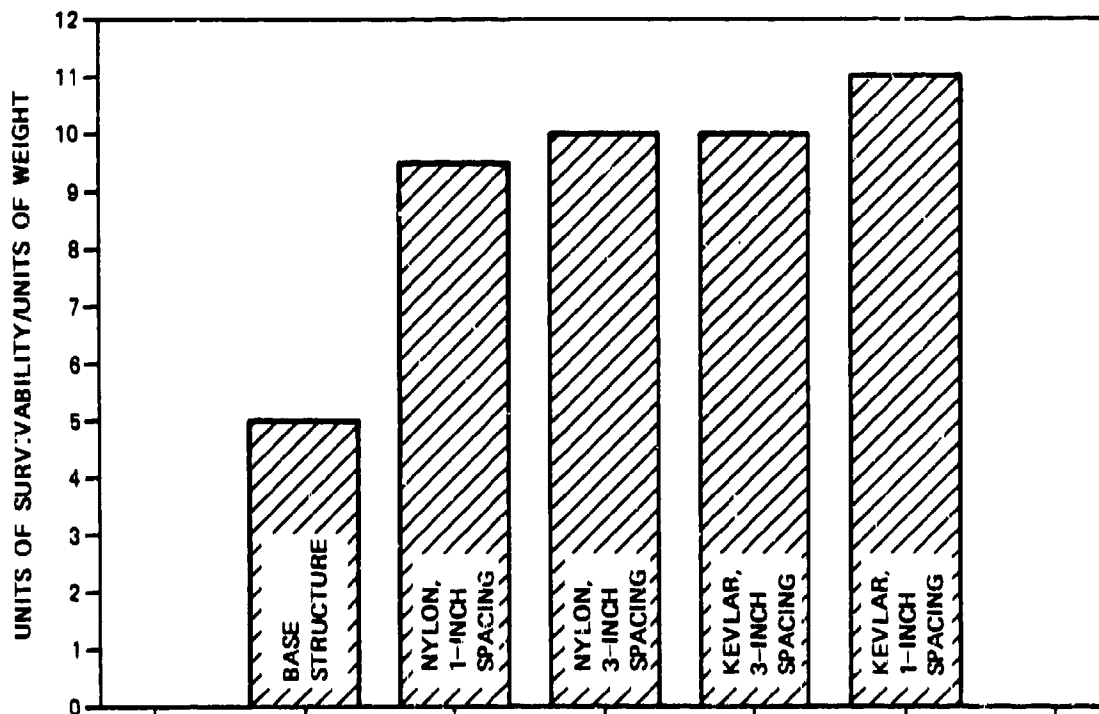


Table 5 shows the results of each test. Table 6 shows the relative survivability of the most successful strip grid panels. Figures 19 through 21 show these panels in descending order, from least vulnerable to more vulnerable.

Layers. Adding complete layers of cloth or foam to the base graphite panel was the third structural configuration tested. The panels using a foam layer between base layers (panels 217 (Figure 22) and 218 (Figure 23)) broke into several pieces and were a drastic failure. Also considered a failure was panel 211, which had a layer of Kevlar and foam. This panel experienced severe cracking and had the ring clamp not been present, the layer of Kevlar would have completely delaminated (Figures 24 and 25). The use of foam within the composite layup is the least survivable layer concept. However, the use of foam as the first layer, next to the fluid, was effective. The idea behind this concept was that the hydraulic ram effect would be dissipated by crushing the foam. This concept, although quite effective in the 100 series testing (Figures 26 and 27), was considered too bulky for tactical aircraft, wasted fuel volume, and weighed nearly twice as much as other concepts showing the same increase in survivability; therefore, it was not included in the 200 series testing.

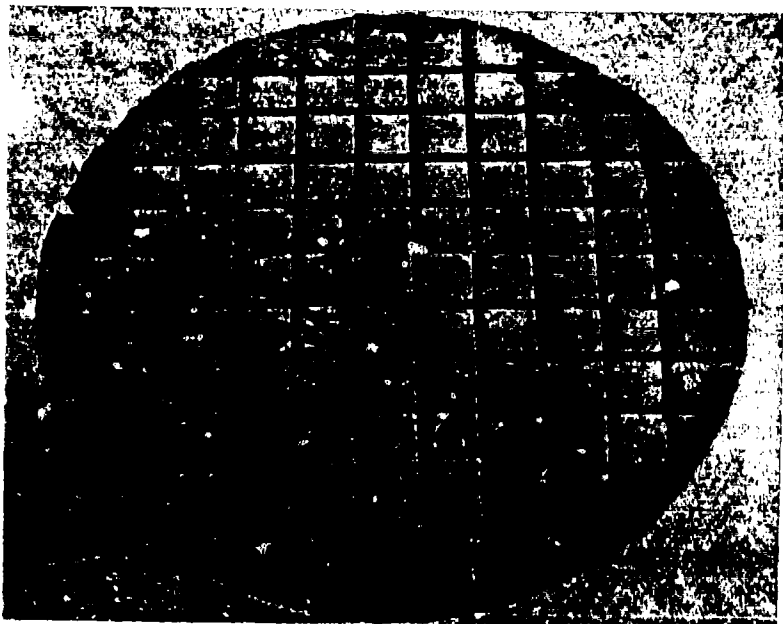


FIGURE 15. Damage Sustained by Kevlar Cord Grid Panel (Grids on 1-Inch Spacing).

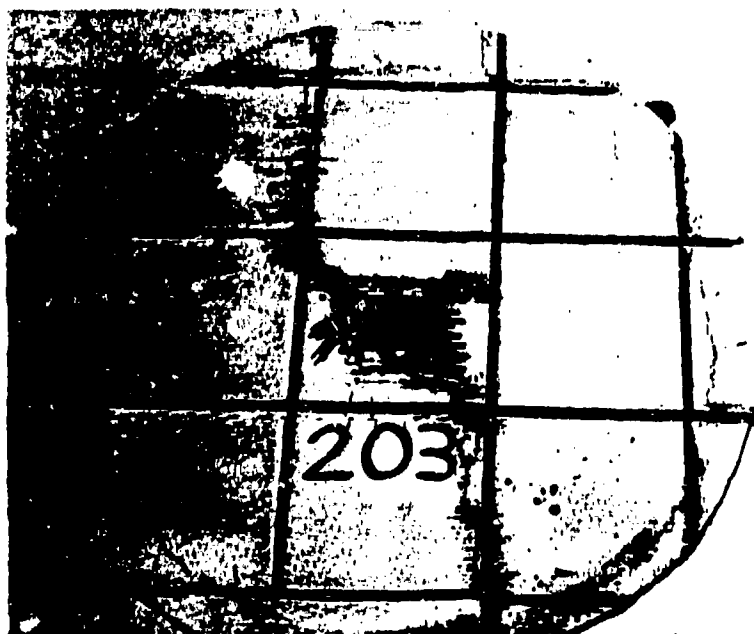


FIGURE 16. Damage Sustained by Kevlar Cord Grid Panel (Grids on 3-Inch Spacing).

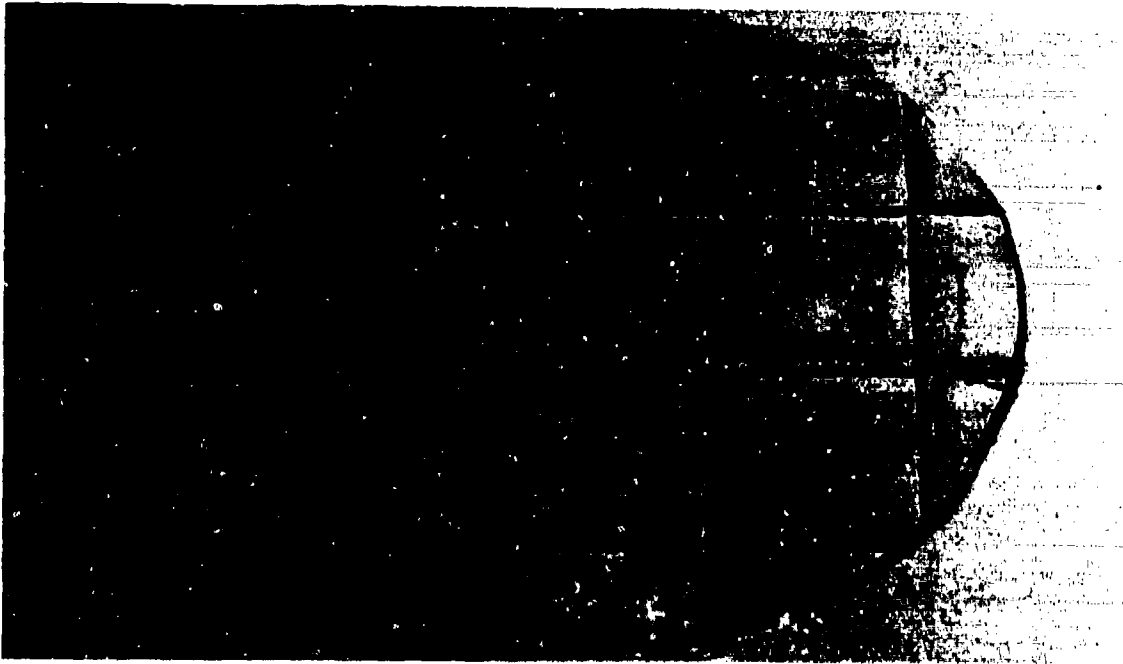


FIGURE 17. Damage Sustained by Nylon Cord Grid Panel
(Grids on 3-Inch Spacing).

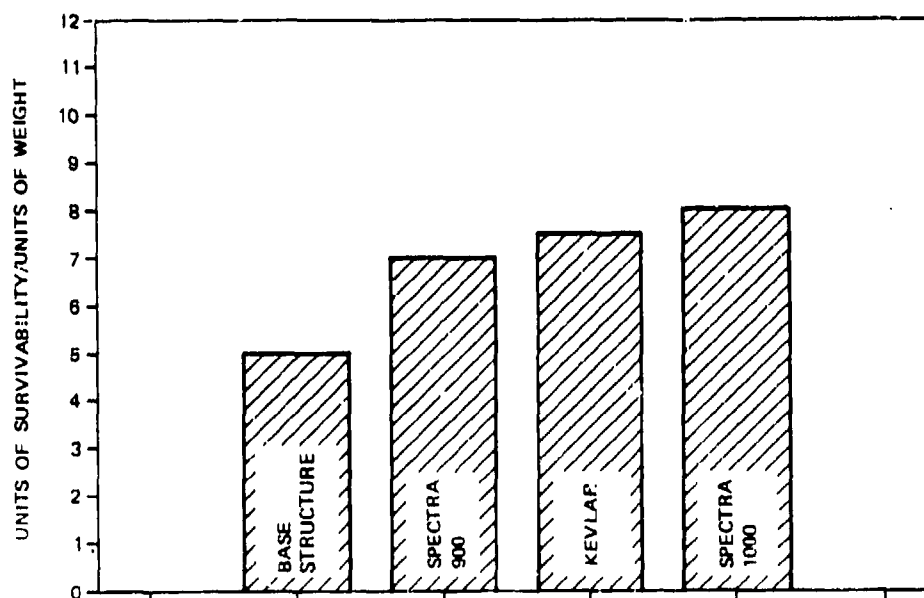


FIGURE 18. Damage Sustained by Nylon Cord Grid Panel
(Grids on 1-Inch Spacing).

TABLE 5. 200 Series Strip Grid Panel Results.

Panel	Description	Weight, gm	Velocity, ft/s	Results
213	Two Kevlar grids, 1-inch wide, 3-inch spacing	268	1915	Severe cracking, severe delamination
207	Three Spectra 900 grids, 1-inch wide, 3-inch spacing	258	1940	Severe cracking, severe delamination, edge shearing
208	Same as 207	268	1900	Severe cracking, severe delamination
225	Same as 207	253	1790	Severe cracking, severe delamination
226	Three Spectra 1000 grids, 1-inch wide, 3-inch spacing	251	1920	Severe cracking, severe delamination
227	Same as 226	254	2030	Severe cracking, severe delamination

TABLE 6. Ranking Table, Strips.



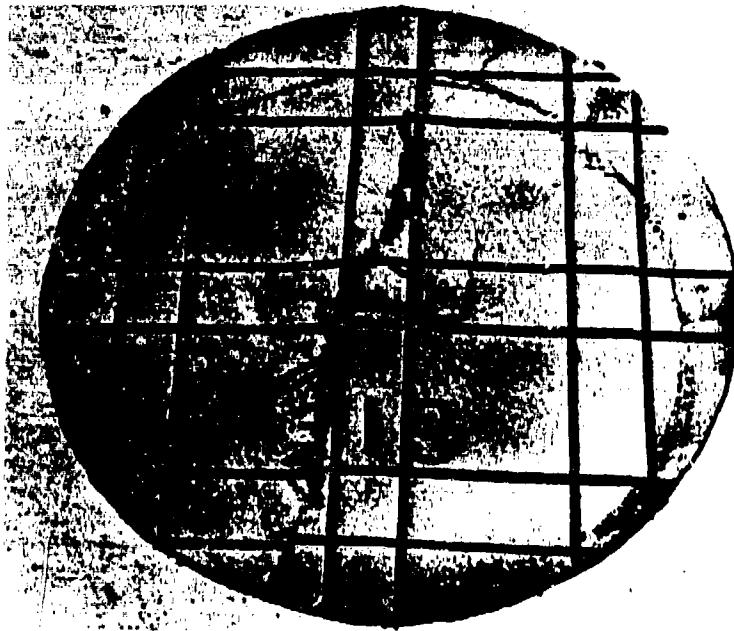


FIGURE 19. Damage Sustained by Spectra 1000 Strip Grid Panel.

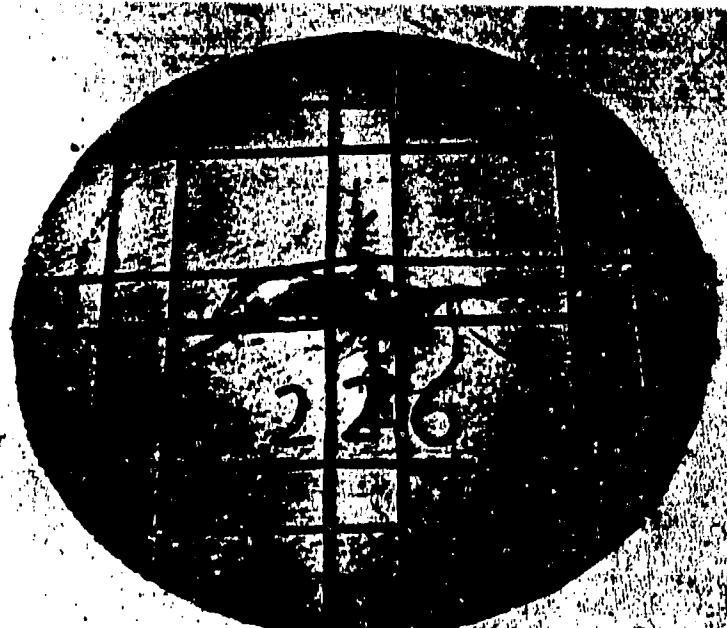


FIGURE 20. Damage Sustained by Kevlar Strip Grid Panel.

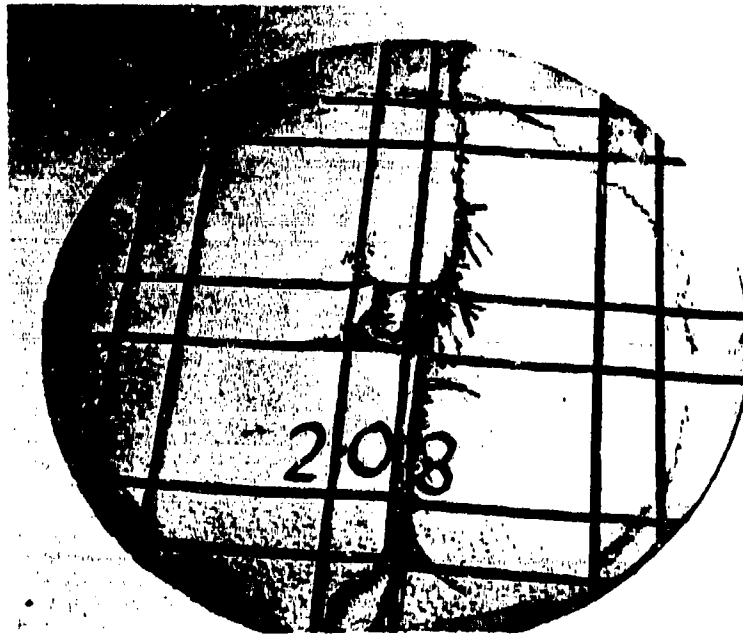


FIGURE 21. Damage Sustained by Spectra 900 Strip Grid Panel.

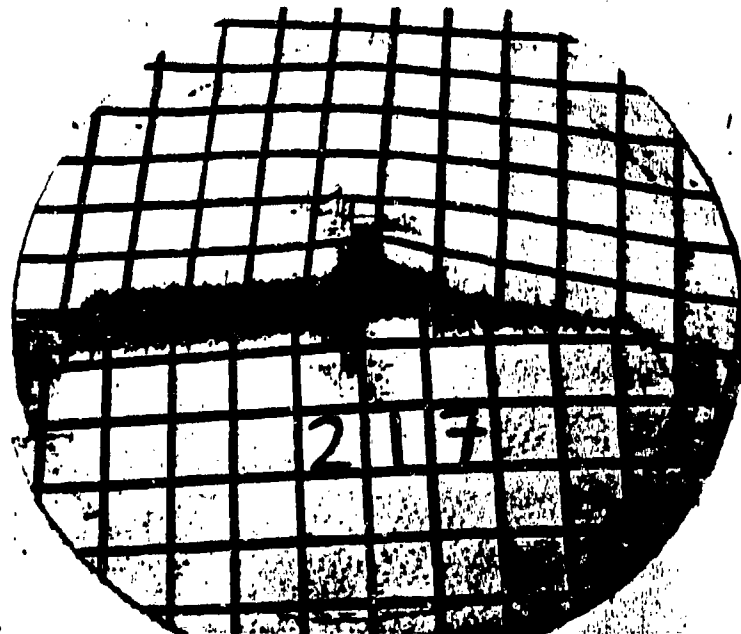


FIGURE 22. Damage Sustained by a Panel With 1/4-Inch of Foam Between Base Layers.

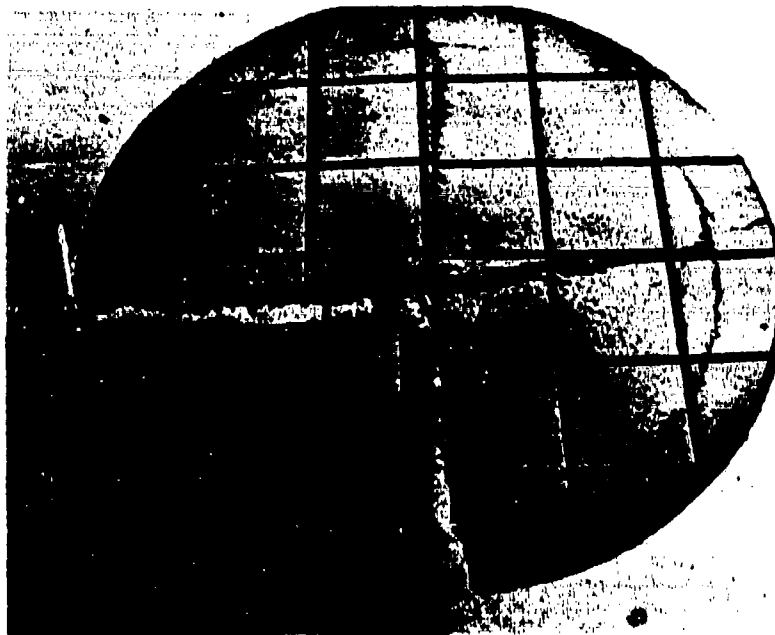


FIGURE 23. Damage Sustained by a Panel With 1/4-Inch of Foam Between Base Layers.

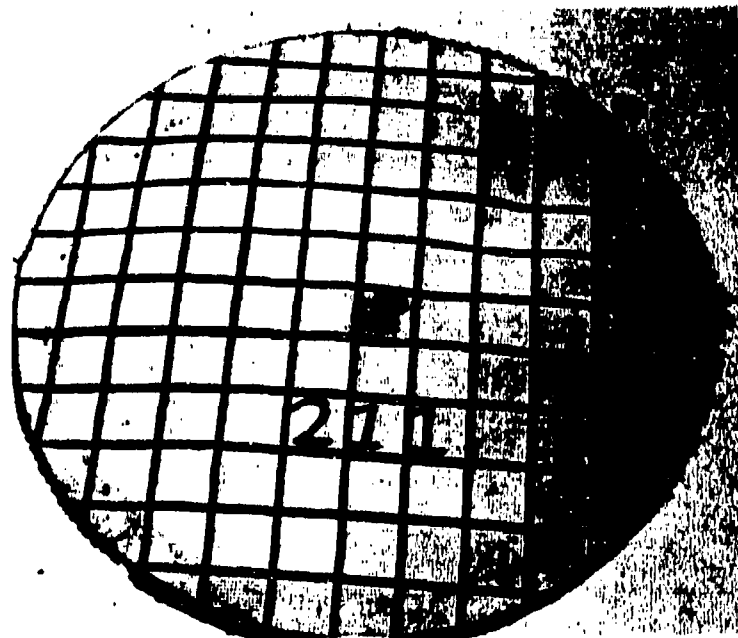


FIGURE 24. Damage Sustained by a Panel With 1/4-Inch of Foam Under a Layer of Kevlar.



FIGURE 25. Delamination of a Panel With 1/4-Inch of Foam Under a Layer of Kevlar.

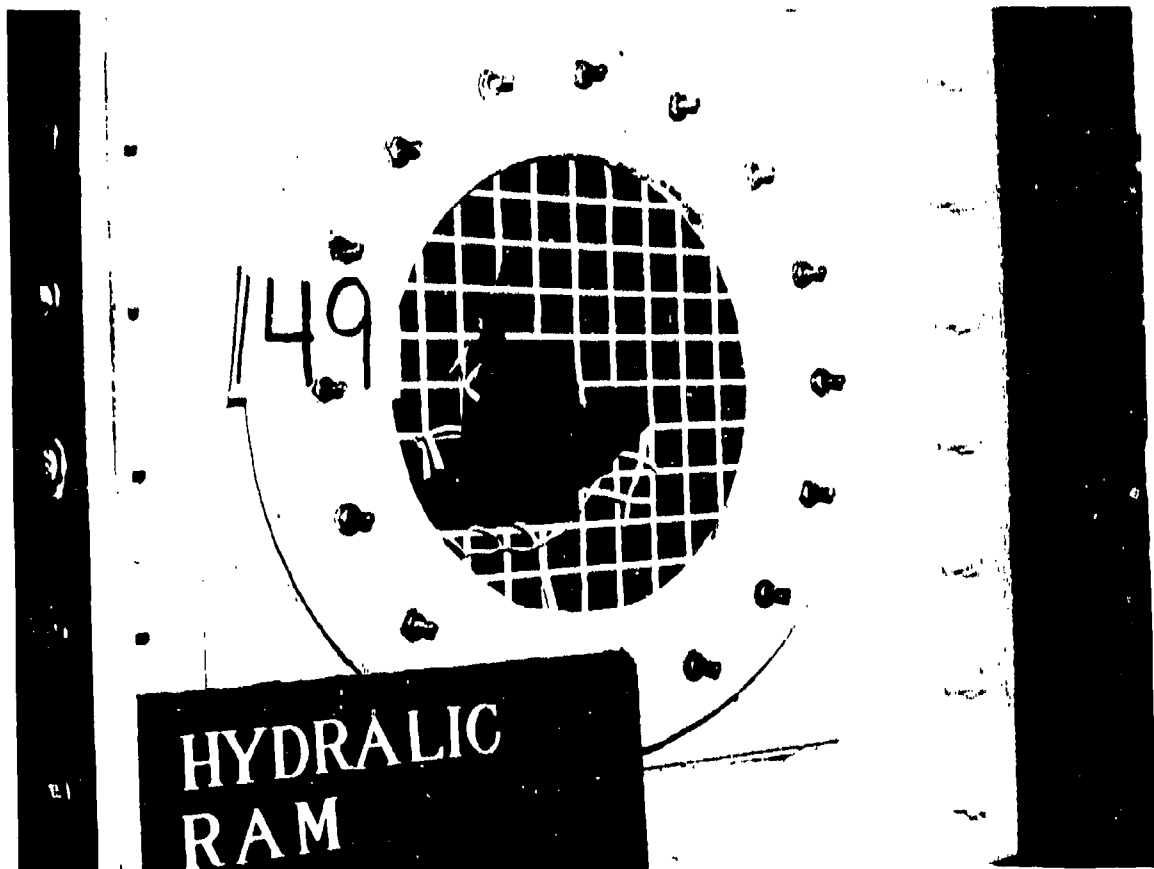


FIGURE 26. Damage Sustained in the 100 Series Testing by a Panel With 1/2-Inch of Foam on the Impact Face.

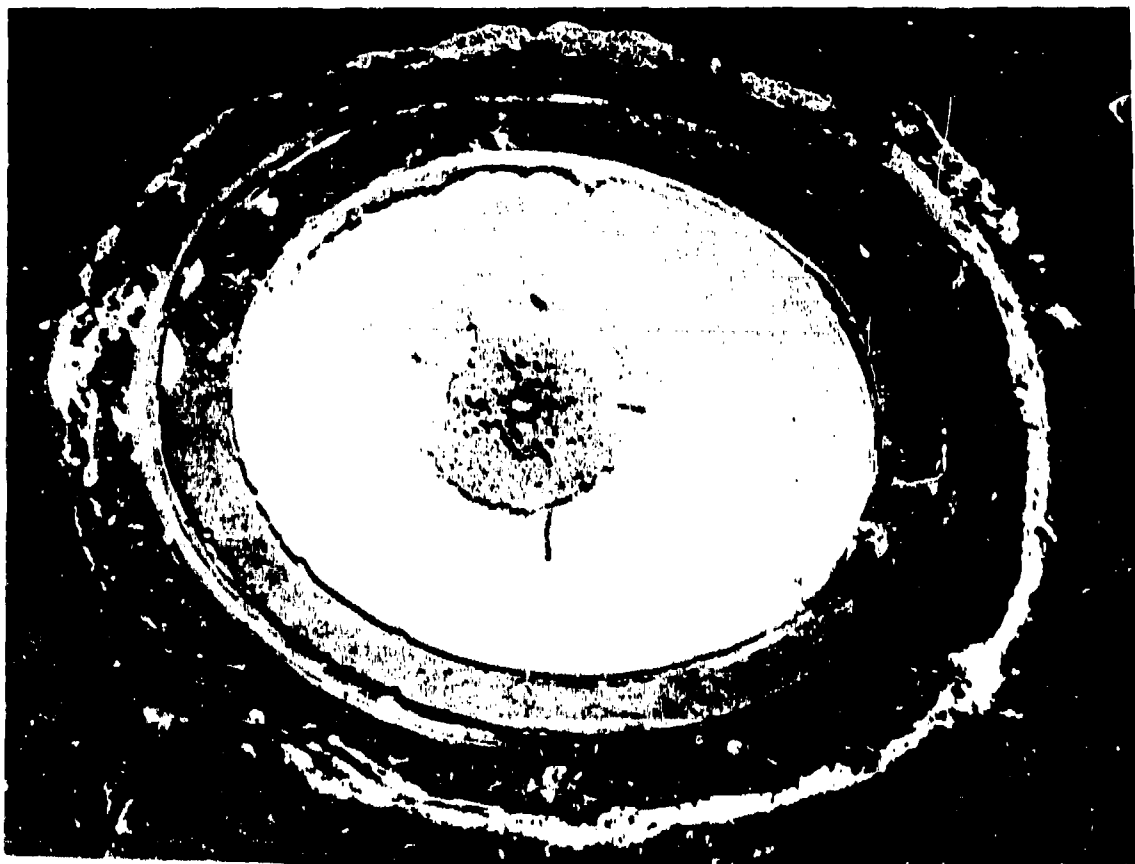


FIGURE 27. Damage Sustained in the 100 Series Testing By a Panel With 1/2-Inch of Foam on the Impact Face.

Of the fabrics tested, Kevlar appeared more survivable than either Spectra 900 or Spectra 1000, which fared about the same. The cracking and delamination were slightly less in the Kevlar structures (panels 209, 212, 214, and 215) than the Spectra structures (panels 204, 205, 221, 222, 223, and 224). There was no appreciable performance difference between having the Kevlar sandwiched inside the structure or as a last layer. The Spectra 1000 appeared to have greater cracking when it was tested inside the structure, but this was accompanied by a decreased amount of delamination. All aspects considered, Spectra 1000 showed essentially the same survivability whether inside or outside the structure. Overall, the most survivable layer concept was the Kevlar, either inside the layup or as the last layer.

Table 7 shows the results of each test. Table 8 shows the relative survivability of the most successful layer panels. Figures 28 through 32 show these panels from least vulnerable to more vulnerable.

TABLE 7. 200 Series Layer Panel Results.

Panel	Description	Weight, gm	Velocity, ft/s	Results
214	Kevlar	263	1945	Severe cracking, severe delamination
215	Same as 214	257	1840	Moderate cracking, minor delamination
209	Kevlar as last layer	253	1920	Severe cracking, severe delamination
210	Same as 209	268	1900	Severe cracking, severe delamination
204	Spectra 900	242	1940	Severe cracking, moderate delamination
205	Same as 204	238	1925	Severe cracking, minor delamination
223	Spectra 1000	249	1940	Severe cracking, severe delamination
224	Same as 223	239	1915	Severe cracking, severe delamination
221	Spectra 1000 as last layer	251	1935	Severe cracking, severe delamination
222	Same as 221	243	1845	Severe cracking, severe delamination
217	1/4-inch foam	263	1915	Drastic failure
218	Same as 217	277	1925	Drastic failure
211	1/4-inch foam inside, Kevlar as last layer	265	1920	Drastic failure

TABLE 8. Ranking Table, Layers.

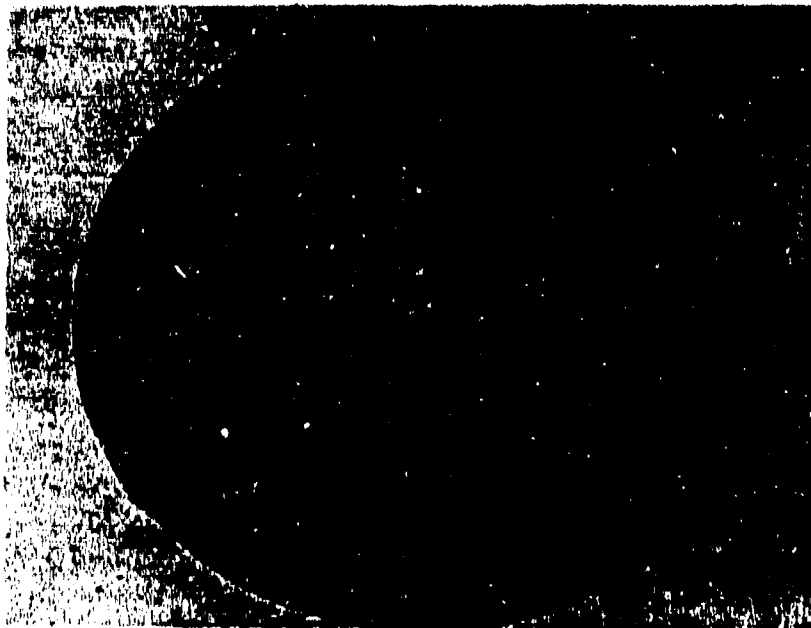
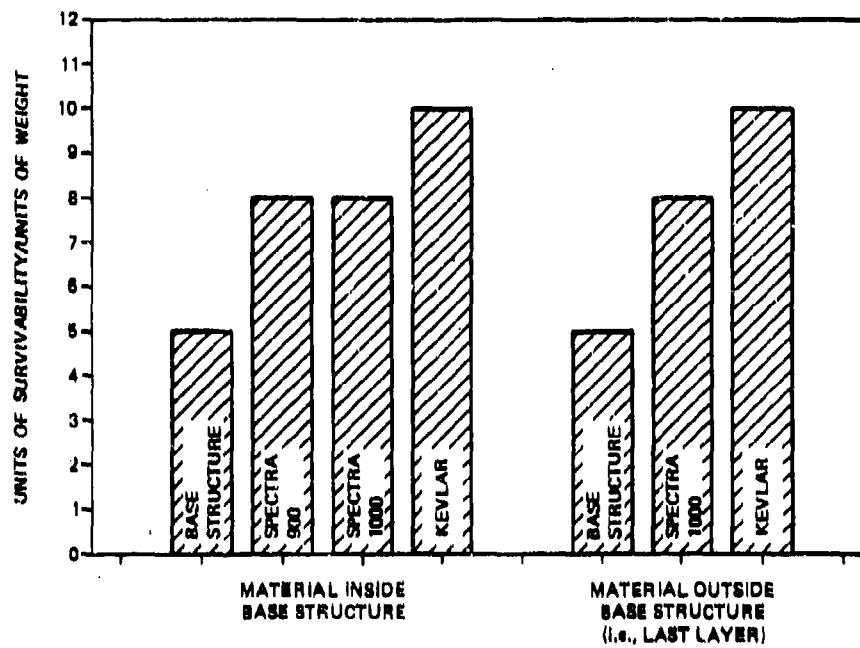


FIGURE 28. Damage Sustained by Kevlar Layer Panel (Kevlar Layer Inside).

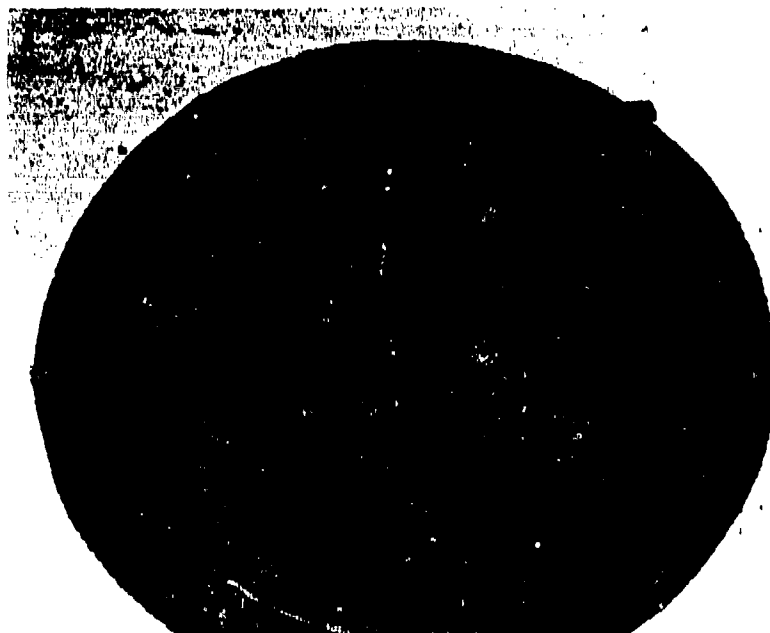


FIGURE 29. Damage Sustained by Kevlar Layer Panel (Kevlar Layer Outside).

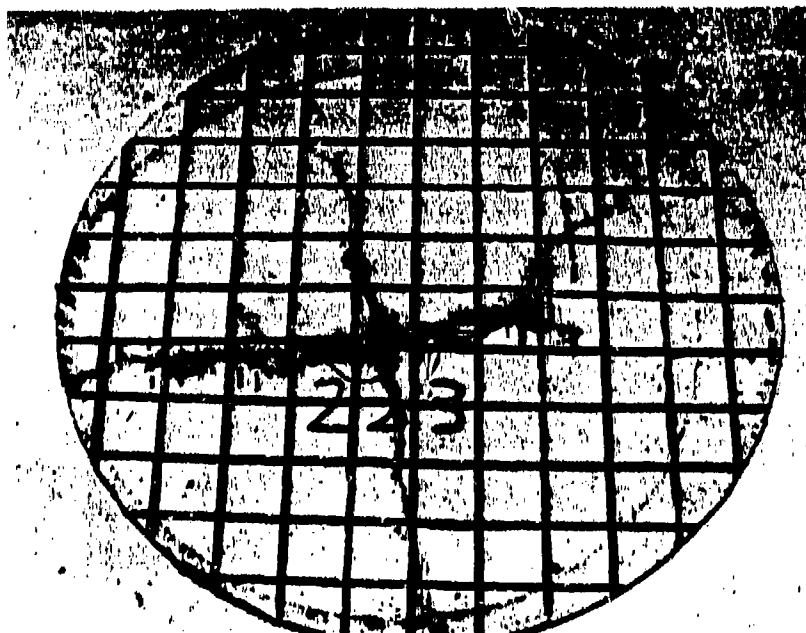


FIGURE 30. Damage Sustained by Spectra 1000 Layer Panel (Spectra Layer Inside).

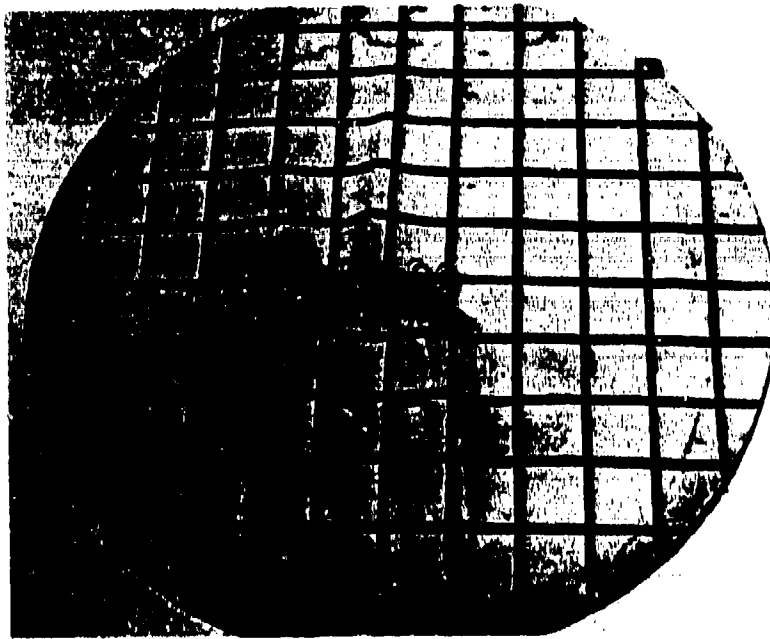


FIGURE 31. Damage Sustained by Spectra 1000 Layer Panel (Spectra Layer Outside).

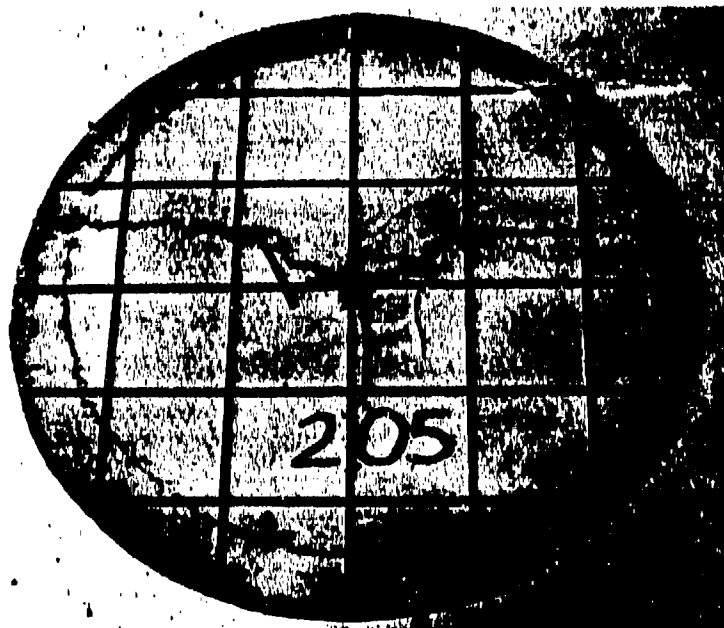


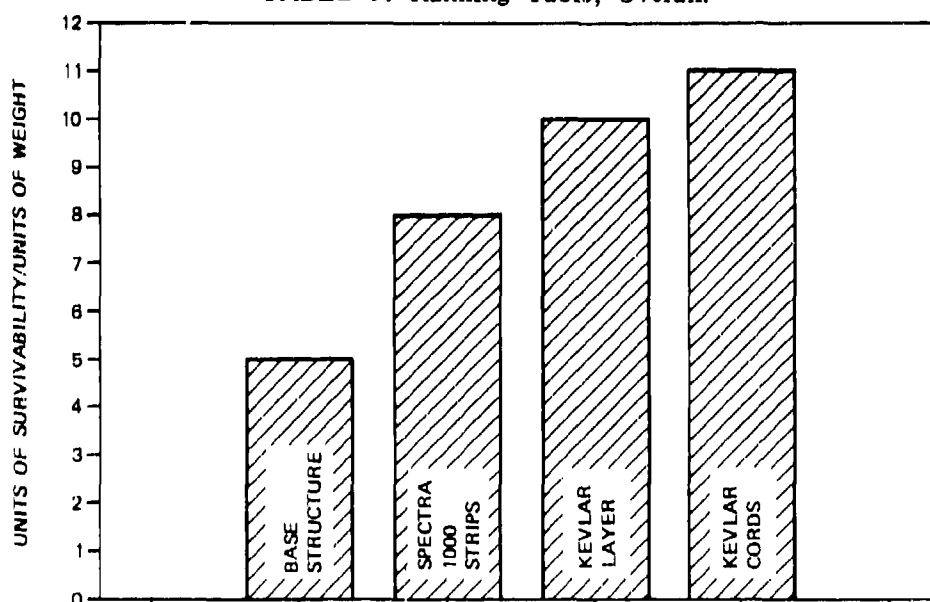
FIGURE 32. Damage Sustained by Spectra 900 Layer Panel (Spectra Layer Inside).

CONCLUSIONS

Due to the relatively small number of panels and hybridization concepts tested thus far, the survivability/vulnerability rankings presented are somewhat tentative. It is clear, however, that all of the concepts mentioned below performed markedly better than unprotected graphite panels. Incorporating any of these concepts would increase the hydraulic ram survivability of a composite panel used in a fuel tank or similar application. The survivability/vulnerability rankings drawn from these tests are presented in graphical form in Table 9. Those rankings are

1. The panels containing a grid of Kevlar cords performed the best overall.
2. Nylon cords performed nearly as well as the Kevlar cords, which indicates that the absolute tensile strength of the cords is not significant for preventing hydraulic ram damage.
3. The performance of the Kevlar layer panels was only slightly worse than the cord panels, but the weight penalty was much more severe.
4. The Kevlar layer panels, whether the Kevlar layer is inside the layup or on top, performed markedly better than either of the Spectra panels or any of the strip configured panels.
5. The strip configured panels were less effective than either of the other hybridizations. The best strip configured panels were comparable to the Spectra layer panels.

TABLE 9. Ranking Table, Overall.



F-18 FUEL TANK PANEL TESTS

TEST SETUP

The test apparatus for these panel tests was a mockup of the No. 4 fuel tank of an F-18, which was originally used for fuel ingestion testing (Figure 33). The composite panels were bolted to the inside of the mockup inlet. The projectile, fired from outside the tank, entered the tank through the aluminum panel visible in Figure 33. The composite panel, inside the mock inlet, was the exit panel for the projectile. The projectile traveled through approximately 3 feet of water in the tank before striking the composite exit panel.

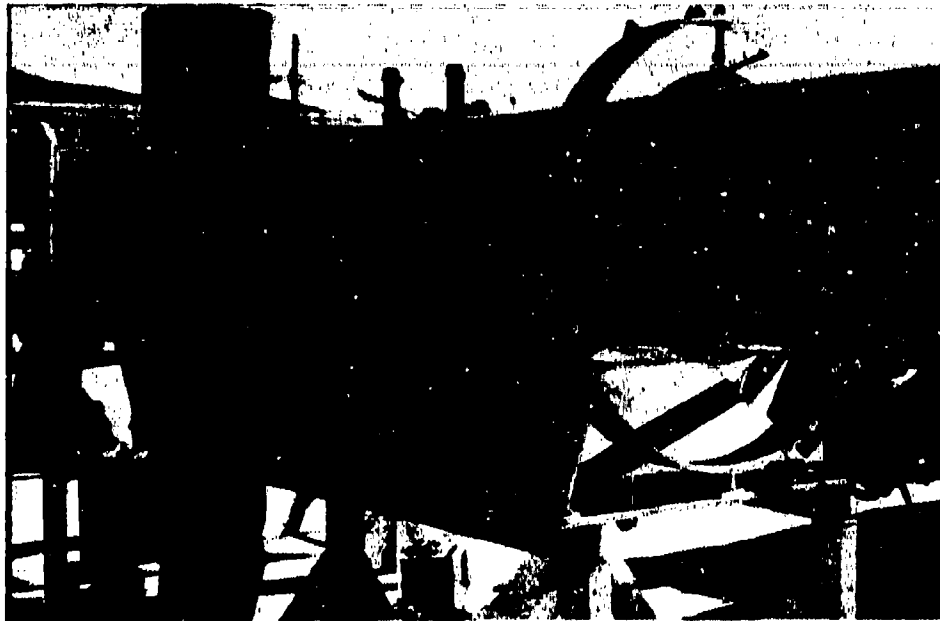


FIGURE 33. F-18 Fuel Tank Mock-Up.

TEST PANEL FABRICATION

The panels were made with 6K denier, five-harness satin, graphite fabric and Epon 828 equivalent resin, arranged in a 0-90/±45/0-90/±45/s layup. The panels were laid up on a tool curved to match the inlet duct, vacuum bagged, and cured at room temperature. A three-cord grid of Kevlar cord was added to panel No. 2. A layer of Kevlar was added to panel No. 3. The baseline panel (No. 1) and the Kevlar layer panel (No. 3) had graphite hat stiffeners bonded to the convex side

(fuel tank interior). The "waffle" surface of the cord grid panel (No. 2) did not allow effective bonding of precured stiffeners and therefore they were omitted. All panels were trimmed to fit the fuel ingestion test fixture (approximately 21 inches along the curve, 16 inches across) and holes were drilled to match those used in the test fixture, at approximately 1 1/2-inch spacing around the perimeter of the panel.

EVALUATION TECHNIQUE

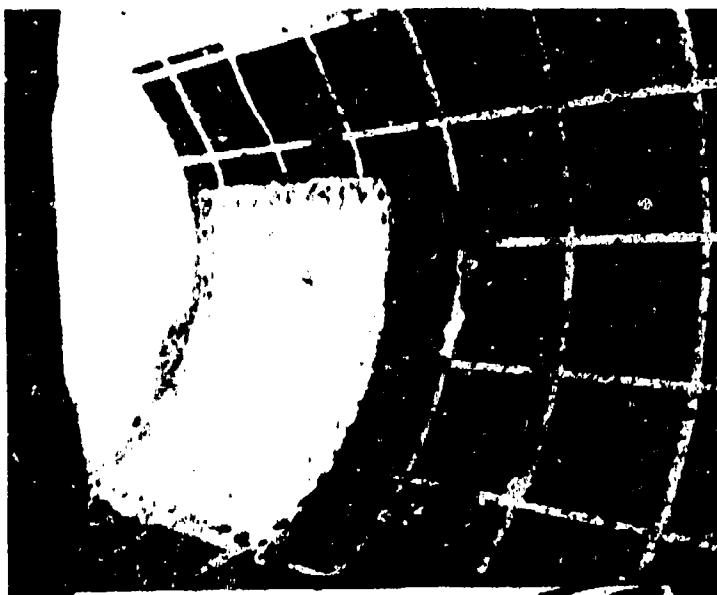
The techniques used to evaluate the damage sustained by the F-18 fuel tank panels were essentially the same as those used for the 12-inch-diameter panels. A visual inspection was made to determine the extent of the cracking, and a coin-tap test was performed to determine the extent of the delamination. Damage zones, like those used for evaluating the 12-inch panels, were used to quantify the damage sustained by the panels. The size of the zones was doubled. The 4-inch-diameter minor damage zone became a 4-inch radius zone, etc.

TEST RESULTS

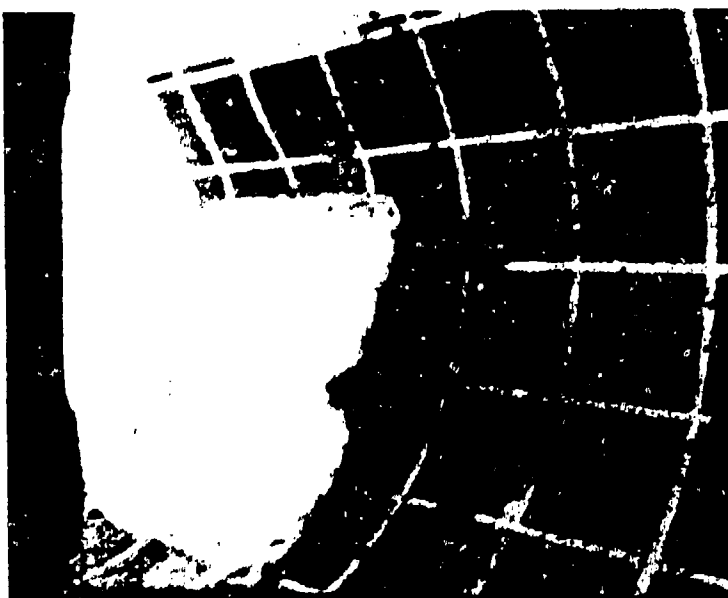
The first panel tested was the all-graphite baseline panel. The projectile chosen was a 14.5-mm API (armor-piercing incendiary) round. The first projectile fired tumbled upon entering the water and veered off the expected trajectory by roughly 45 degrees, missing the panel completely. The stiffeners, adhesively bonded to the tank side of the panel, were removed by the hydraulic ram. Several bolt heads pulled through the panel but the panel appeared to be otherwise undamaged. The panel was resecured to the test fixture, adding washers at the bolt locations that had previously pulled through the panel.

The second shot at the baseline panel also veered appreciably from its expected trajectory, striking the panel very near the edge. The damage to the panel was fairly extensive. The panel cracked and buckled at the point of impact (Figure 34). Most of the bolts either pulled through the panel or sheared off. The panel delaminated only slightly. The extent of the cracking was rated as severe, extending more than 8 inches from the point of impact (Figure 35). Delamination was rated minor.

At this point, it was decided that the variability of the 14.5-mm projectile's trajectory through the 3 feet of water in the tank would not provide comparable data from panel to panel. The 14.5-mm projectile retained its pointed shape after passing through the aluminum entry panel and veered off its trajectory unpredictably. Therefore, the round was changed for the Kevlar protected panels. A 23-mm API round was chosen. The point of the 23-mm API projectile was of a different design than the 14.5-mm round. The thin aluminum entry plate removed the point from the 23-mm projectile so that when it entered the water, it was essentially a right-circular cylinder.

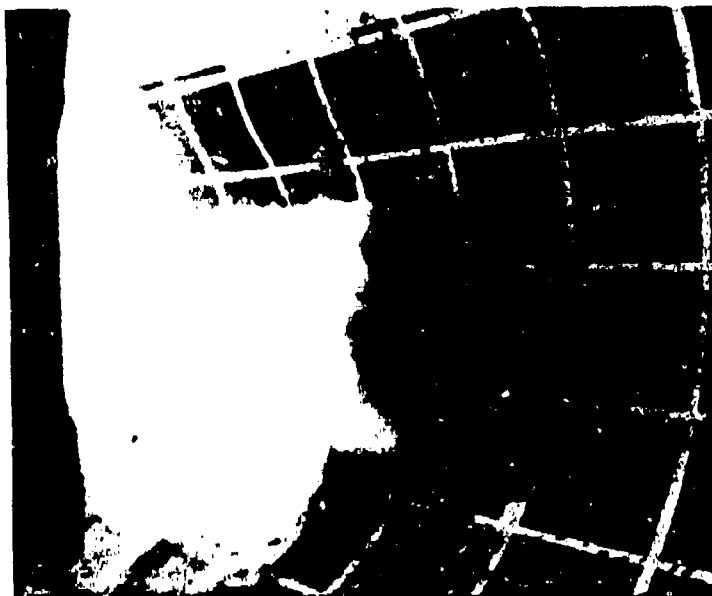


(a)

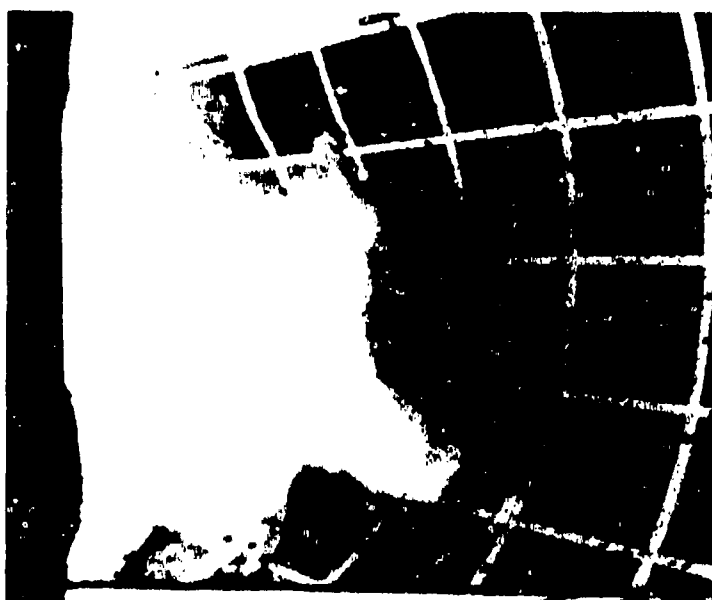


(b)

FIGURE 34. High-Speed Film of Hydraulic Ram Damage Occuring.

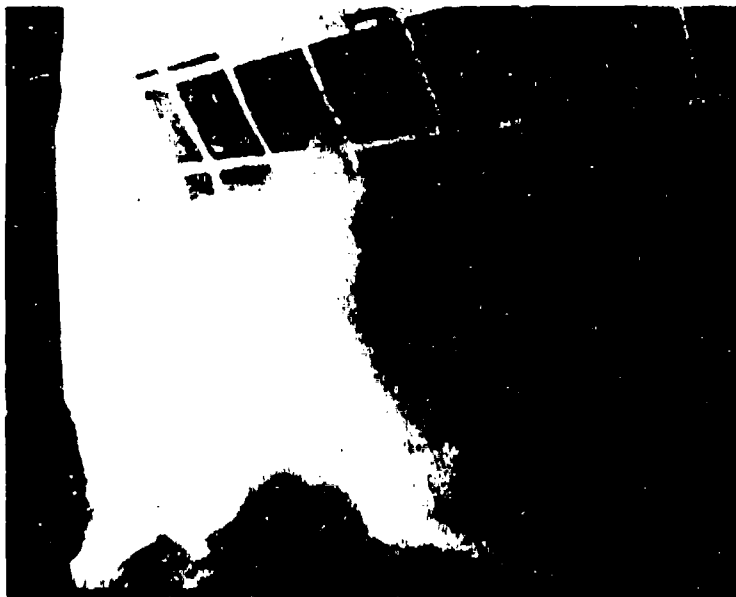


(c)



(d)

FIGURE 34. (Contd.)



(e)

FIGURE 34. (Contd.)

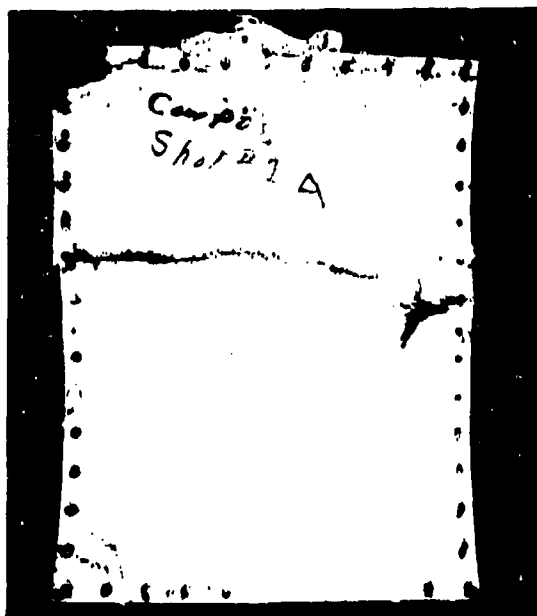
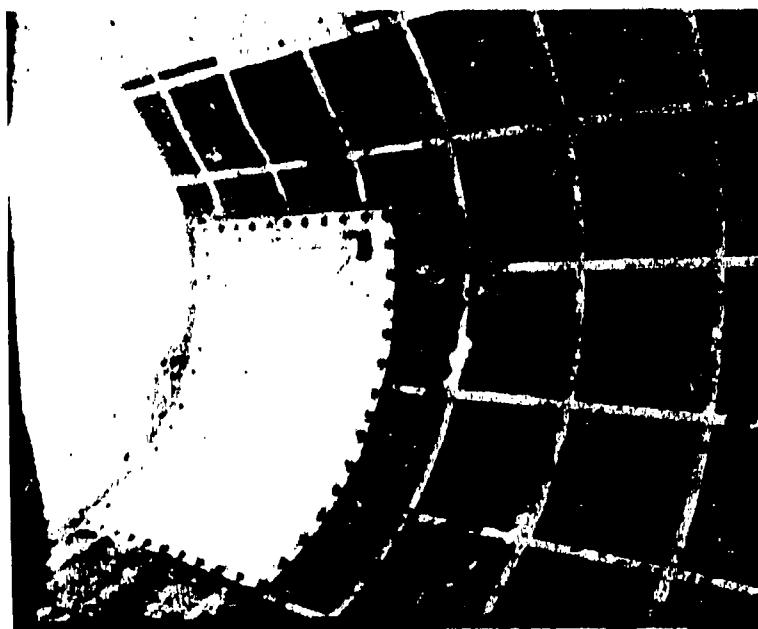


FIGURE 35. Damage Sustained by
Baseline Panel Subjected to Hydraulic
Ram From 14.5-mm API Round.

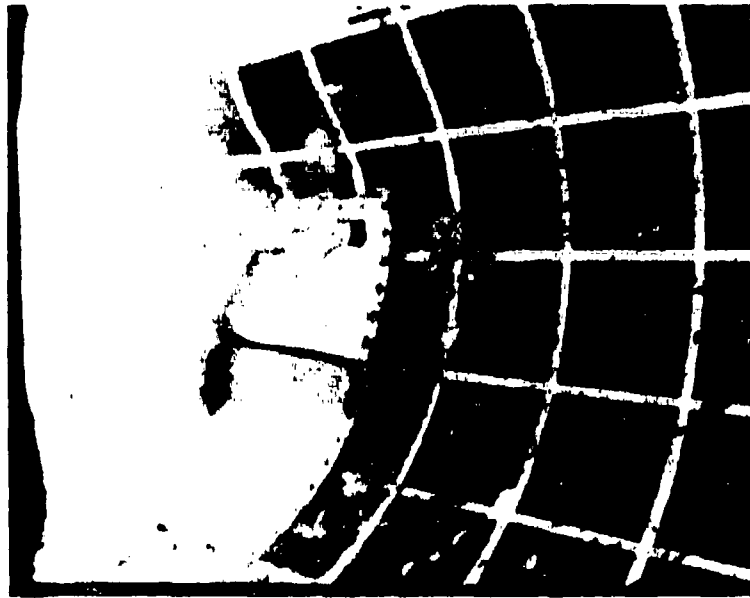
The second panel tested contained the grid of Kevlar cords. The 23-mm API projectile struck the panel near dead center, causing extreme damage (Figure 36). The panel cracked and buckled both vertically and horizontally from the point of impact. The cracks extended to three of the four edges of the panel. The upper right quarter of the panel was held to the rest of the panel only by the Kevlar cords extending down to the lower right quarter (Figure 37). Nearly three quarters of the panel delaminated. Due to the loss of all structural value, this panel was classified as a drastic failure. Both the cracking and delamination extended through the severe rating zone.

The third panel contained a layer of Kevlar fabric. It was also shot with a 23-mm API round that struck the center of the panel, and like panel No. 2 caused the panel to crack and buckle horizontally and vertically from the point of impact (Figure 38). The cracks on panel No. 3 only reached two edges. The lengths of the cracks were long enough to reach the severe damage zone. Delamination was contained within the minor zone, except for one small area that extended into the moderate damage zone. As was the case on the baseline panel, the adhesively bonded stiffeners were blown off of the panel by the hydraulic ram. The overall rating of panel No. 3 would be severe damage.

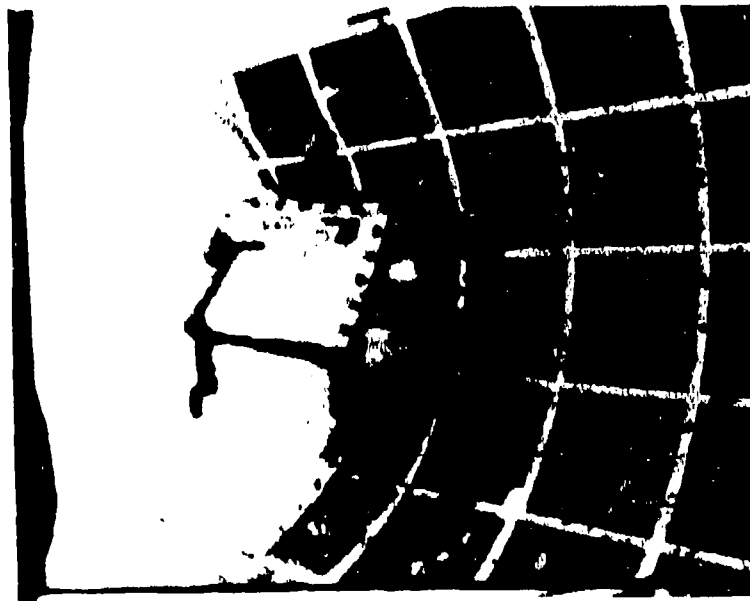


(a)

FIGURE 36. High-Speed Film of Hydraulic Ram Damage Occuring.

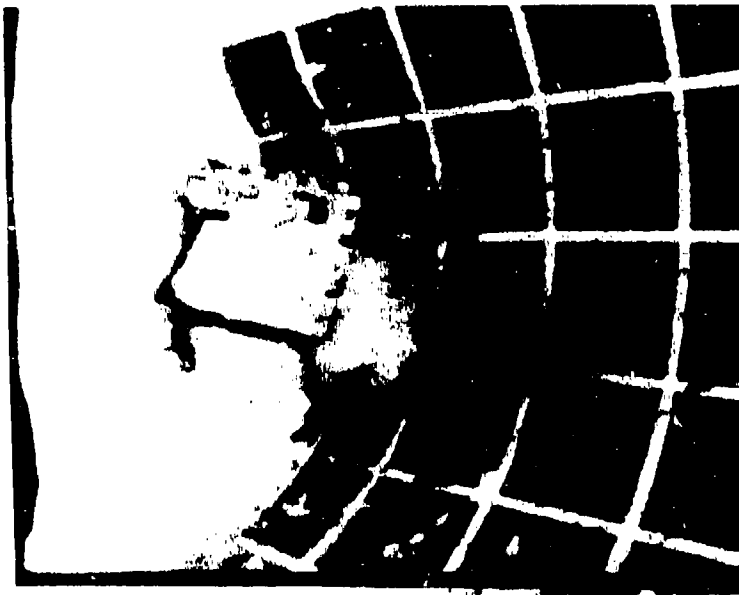


(b)

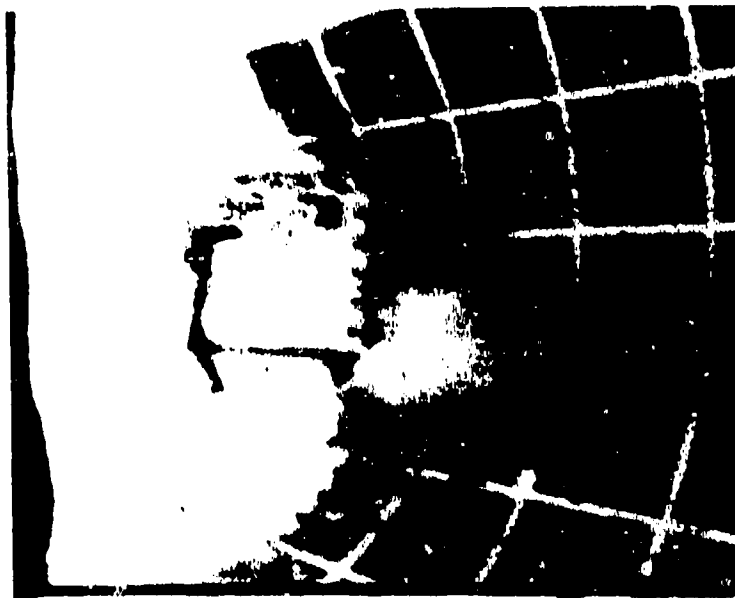


(c)

FIGURE 36. (Contd.)



(d)



(e)

FIGURE 36. (Contd.)

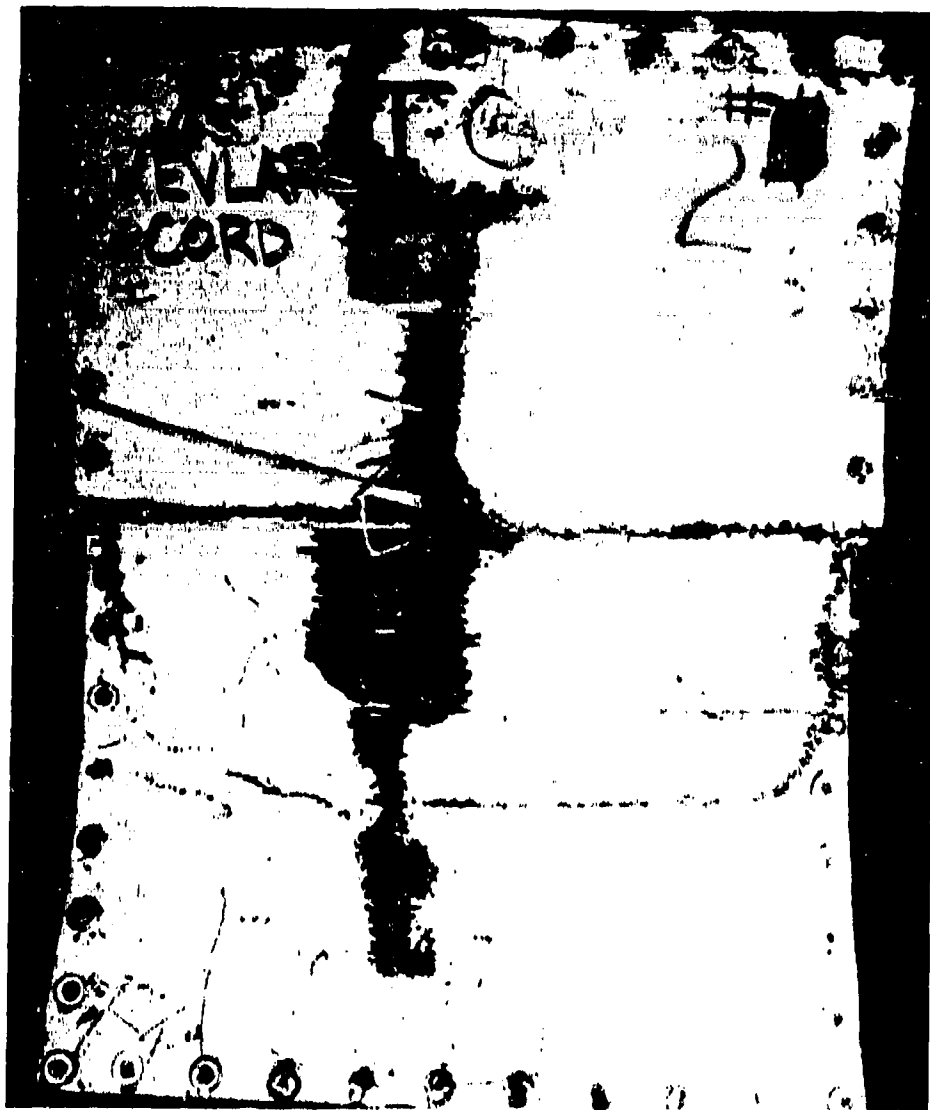


FIGURE 37. Damage Sustained by Kevlar Cord Grid Panel
Subjected to Hydraulic Ram From 23-mm API Round.

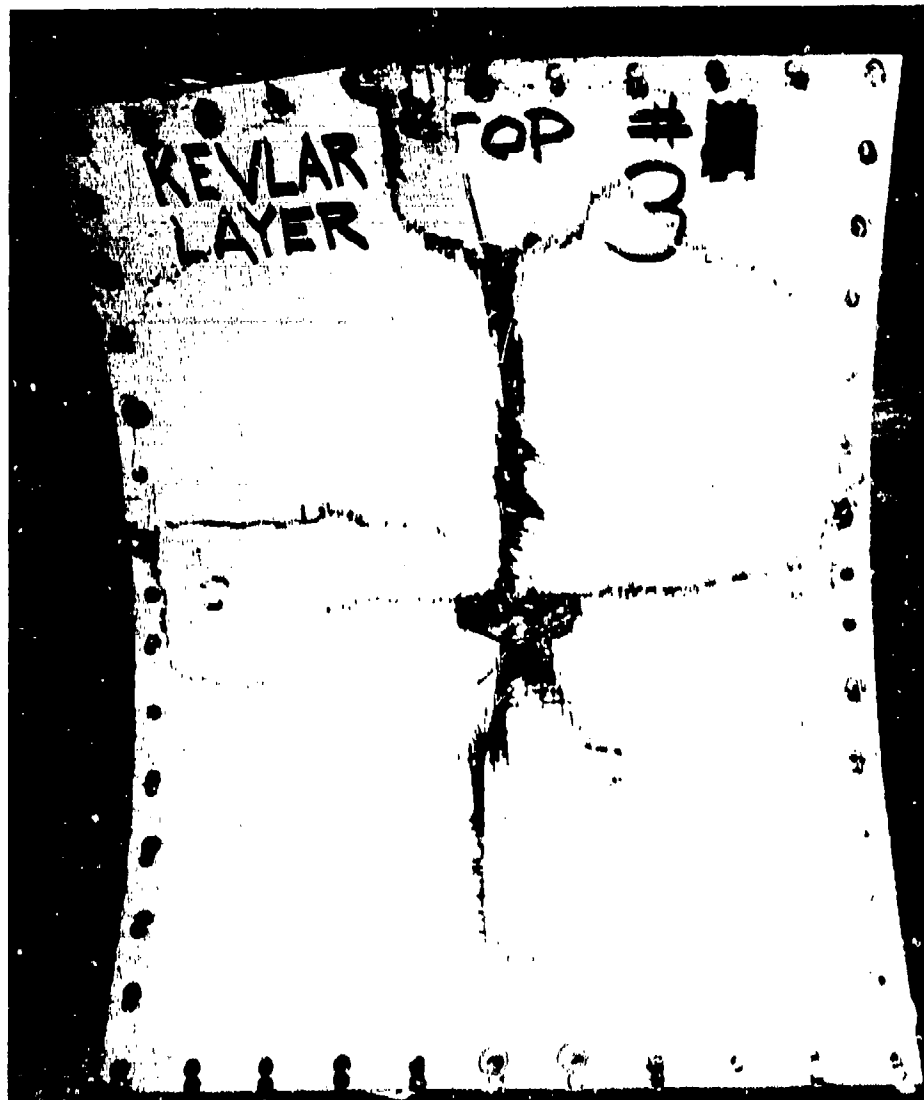


FIGURE 38. Damage Sustained by Kevlar Layer Panel
Subjected to Hydraulic Ram From 23-mm API Round.

CONCLUSIONS

Realistic conclusions are not really obtainable from a data base this small. It should be noted, however, that the survivability/vulnerability order among the hybridizations tested with these panels does not agree with that determined in the 12-inch-diameter panels discussed earlier. While both of the hybridizations sustained severe damage in these tests, the panel that contained the Kevlar layer survived the hydraulic ram slightly better than the panel containing the Kevlar cord grid.

Unfortunately, no direct comparison can be made between the baseline panel (shot with a 14.5-mm API) and the Kevlar protected panels (shot with 23-mm API rounds).

RECOMMENDATIONS FOR FUTURE HYDRAULIC RAM TESTING

1. Complete further testing to verify the survivability/vulnerability rankings reported.
2. Develop more realistic tests of composite aircraft structure survivability.
 - a. Investigate more large-scale panels (like those used in the F-18 tests) in which edge conditions are not as much of a factor.
 - b. Develop an active-load test fixture that will allow hydraulic ram test specimens to be loaded to simulate a realistic flight environment.
3. Improve the damage rating system.
 - a. Develop a residual strength test.
 - b. Investigate the use of nondestructive test procedures.
4. Continue investigating new hybridization concepts and materials.
 - a. Sew together layers of materials that have shown delamination.
 - b. Further evaluate the effect of using tougher matrix and reinforcing materials.
 - c. Investigate the effect of production methods.

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- 1 Lockheed-California Company, Burbank, CA (D. Tuttle)
- 1 Lockheed-Georgia Company, Marietta, GA (L. Stephens)
- 1 McDonnell Douglas Aircraft Company, Long Beach, CA (A. Parker)
- 1 McDonnell Douglas Astronautics Company, Huntington Beach, CA (B. Cooper)
- 1 McDonnell Douglas Corporation, St. Louis, MO (R. Detrich)
- 1 McDonnell Douglas Helicopter Company, Mesa, AZ (Library 530/B223)
- 3 Naval Air Development Center, Warminster
 - Code 60133, A. E. Simkins (1)
 - Code 604, Dr. S. L. Huang (1)
 - Code 6043, T. E. Hess (1)
- 1 Naval Air Engineering Center, Lakehurst (Code 9332, D. Zreblec)

- 9 Naval Air Systems Command
 - AIR-5004/5004E (1)
 - AIR-5164, D. Atkinson (5)
 - AIR-5164J, LTCOL J. Sebolka (1)
 - AIR-53031G (1)
 - AIR-5304C1 (1)
- 1 Naval Surface Weapons Center, Silver Spring (Code E232, L. Clemens)
- 13 Naval Weapons Center, China Lake
 - Code 3381, C. Padgett (12)
 - Code 3383, S. Lang (1)
- 1 Northrop Corporation, Aircraft Division, Hawthorne, CA (J. Reynolds)
- 1 Orlando Technology, Incorporated, Shalimar, FL (R. Grove)
- 1 Reynolds Metals Company, Richmond, VA (S. Sunday)
- 2 Rockwell International Corporation, Los Angeles, CA
 - W. Darling (1)
 - Dr. T. Logan (1)
- 1 Sikorsky Aircraft, Stratford, CT (J. Fansler)
- 1 Southwest Research Institute, San Antonio, TX (P. Zabel)
- 1 Swedlow, Incorporated, Garden Grove, CA (Technical Library)
- 1 System Planning Corporation, Arlington, VA (Library)
- 1 Systron Donner, Concord, CA (B. Kauthane)
- 1 Teledyne Ryan Aeronautical, San Diego, CA (Technical Library)
- 1 The Service Engineering Company, Bel Air, MD
- 1 Uniroyal Plastics Company, Incorporated, Mishawaka, IN (J. Kulesia)
- 1 United Technologies Corporation, East Hartford, CT (Library, M. Donnelly/Reports)
- 1 University of Dayton, Research Institute, Technical Information Services, Dayton
 - OH (S. Bliss)
- 1 University of Denver, Denver Research Institute, Laboratories for Applied Mechanics, Denver, CO (C. Hoggatt)